2-4-2010

An economic breakeven model of cellulosic feedstock production and ethanol conversion with implied carbon pricing

John Miranowski
Iowa State University, jmirski@iastate.edu

Alicia Rosburg
Iowa State University, arosburg@iastate.edu

An economic breakeven model of cellulosic feedstock production and ethanol conversion with implied carbon pricing

Abstract
The objectives of this paper include: 1) developing an economic framework to estimate long run equilibrium breakeven prices that cellulosic ethanol processors can pay for the marginal or last unit of biomass feedstock they purchase and still breakeven and that cellulosic feedstock producers need to receive for supplying the last unit of feedstock delivered to a commercial-scale plant; 2) estimating the gap or difference between the biorefinery's willingness to pay (WTP) or derived demand for the last unit of cellulosic feedstock and the suppliers' willingness to accept (WTA) or marginal cost (MC) of supplying the last unit of feedstock; 3) completing a life-cycle analysis (LCA) of each feedstock alternative or a "well-to-wheels" accounting of the potential greenhouse gas (GHG) savings associated with feedstock-specific ethanol relative to gasoline; and 4) calculating the carbon price or credit necessary for a biofuel market to exist in the long run. The model is designed to address various policy issues related to cellulosic biofuel production, including cellulosic biofuel production costs, the cost of cellulosic feedstock production when accounting for all costs incurred, government intervention costs either through tax credits and other incentives needed to sustain biofuel markets or through mandates to achieve the revised Renewable Fuels Standard (RFS.2), and finally, the implicit price or credit for CO2e embodied in cellulosic biofuel.

Keywords
sustainable energy, biofuels, feedstock, ethanol, cellulosic feedstock, carbon pricing

Disciplines
Economics

An Economic Breakeven Model of Cellulosic Feedstock Production and Ethanol Conversion with Implied Carbon Pricing

John Miranowski[1] and Alicia Rosburg[2]

Iowa State University
Department of Economics
Working Paper

February 2010

[1] Miranowski: Professor, Department of Economics, 382B Heady Hall, Iowa State University, Ames Iowa 50011; Phone: (515) 294-6132; Fax: (515) 294-0221; Email: jmirski@iastate.edu

[2] Rosburg: PhD Student, Department of Economics, 165 Heady Hall, Iowa State University, Ames Iowa 50011; Phone: (515) 294-3512; Email: arosburg@iastate.edu

1. Introduction

Growing interest in sustainable energy and energy independence is evident by a simple Google search on the phrase "Go Green," yielding 162 million hits. With the growing emphasis on finding ways to be environmentally responsible and reduce greenhouse gas (GHG) emissions, interest has reemerged in biofuels, particularly ethanol, in the past twenty-five years. U.S. ethanol production has increased from 175 million gallons in 1980 to over 10 billion gallons at the beginning of 2009 [RFA, 2010]. Part of this rapid growth has been driven by the various incentives and mandates placed on biofuel industries, including the MTBE phase-out when no liability protection was provided, and other efforts to regulate mobile-source emissions into the environment. New incentives and mandates continue to emerge, encouraging expansion in industry development.[3]

We have now entered a new biofuels era. The food versus fuel debate began in 2007, followed by the passage of the Energy Independence and Security Act of 2007 (EISA) with the revised Renewable Fuels Standard (RFS.2) mandating increasing levels of biofuels, especially from cellulosic biomass, through 2022. Under the EISA, the Environmental Protection Agency (EPA) is responsible not only for insuring that the mandate is met, but also that new plants processing biofuel from different feedstock categories (e.g., cellulose) meet the legislated low carbon fuel standard (LCFS) for that type of biofuel production.[4] Additionally, the Food, Conservation, and Energy Act of 2008 (FCEA) established a $1.01/gallon tax credit for cellulosic ethanol producers, and contained incentives for feedstock producers as well. The new legislation mandates that cellulosic biofuels be part of the liquid transportation fuel mix and contribute to reducing our carbon footprint. The mandate to blend cellulosic biofuels, which begins in 2010 and reaches 16 billion gallons by 2022, could have serious cost implications for the American public. But our knowledge is limited on the economics of producing cellulosic biofuels, because no commercial cellulosic biorefinery exists and cellulosic biomass production is typically smaller scale than conventional crop production. Our understanding of the

[3] English et al., 2006; Berdahl et al., 2005; The White House, 2007

[4] For example, new corn ethanol plants must be certified to achieve a LCA GHG reduction of 20% over gasoline and cellulosic ethanol a 60% reduction relative to gasoline, including land use change (LUC) impacts on GHG emissions. To meet the RFS.2 for biofuels may require that the biomass feedstock be produced in ways that contribute to achieving the LCFS pertaining to the biofuel.

implications of RFS.2 requires a better understanding of the economics of producing cellulosic ethanol.

Corn has been the leading feedstock in the U.S. ethanol industry, accounting for approximately 97% of all ethanol production [Eidman, 2007]. Given cropland constraints and the increasing cost of supplying feedstock to the corn ethanol industry with competing demands from the livestock industry and other users, cellulosic material has emerged as a potential alternative feedstock for biofuels. Because cellulosic ethanol feedstock is in the early stages of industry development, this analysis focuses on research estimates of the costs and benefits of cellulosic ethanol production using alternative cellulosic feedstocks grown under different climatic and environmental conditions.

Several studies have been undertaken of cellulosic feedstock costs in recent years. An early effort that attracted much attention was the USDA/DOE's Billion Ton Study [USDA/DOE, 2005]. In that analysis, feedstock costs became the residual claimant in the cost allocation process and were valued at about $35 per ton.[5] Likewise, the University of Tennessee's "25x25" Study used a range of values on the low end of recent research estimates [English et al., 2006]. Several recent studies of biomass production costs have reported substantially higher costs of biomass production.[6] Further, most previous studies have not attempted to estimate what cellulosic biofuel producers could afford to pay for biomass feedstock.

We construct a simple breakeven model that represents the feedstock supply system and biofuel refining process to evaluate the feasibility of a cellulosic ethanol market from six biomass feedstocks: corn-stover, switchgrass, *Miscanthus*, wheat straw, prairie grass and woody biomass. Feasibility of a cellulosic ethanol market is determined by the relationship between the biofuel processor's and biomass supplier's breakeven values for the last unit of biomass supplied to the biorefinery. The breakeven value is evaluated at the last unit of biomass supplied since the processor (i.e. biomass purchaser) must pay the same price for all purchased units. We construct a flexible model framework in order to evaluate several alternative feedstocks, biorefinery characteristics and policy scenarios.

The objectives of this paper include: 1) developing an economic framework to estimate long run equilibrium breakeven prices that cellulosic ethanol processors can pay for the marginal

[5] All biomass weights are measured in short tons (2000 lbs) unless noted otherwise.
[6] See Appendix 1 for a summary of previous research estimates on biomass production cost.

or last unit of biomass feedstock they purchase and still breakeven and that cellulosic feedstock producers need to receive for supplying the last unit of feedstock delivered to a commercial-scale plant; 2) estimating the gap or difference between the biorefinery's willingness to pay (WTP) or derived demand for the last unit of cellulosic feedstock and the suppliers' willingness to accept (WTA) or marginal cost (MC) of supplying the last unit of feedstock; 3) completing a life-cycle analysis (LCA) of each feedstock alternative or a "well-to-wheels" accounting of the potential greenhouse gas (GHG) savings associated with feedstock-specific ethanol relative to gasoline; and 4) calculating the carbon price or credit necessary for a biofuel market to exist in the long run. The model is designed to address various policy issues related to cellulosic biofuel production, including cellulosic biofuel production costs, the cost of cellulosic feedstock production when accounting for all costs incurred, government intervention costs either through tax credits and other incentives needed to sustain biofuel markets or through mandates to achieve the revised Renewable Fuels Standard (RFS.2), and finally, the implicit price or credit for CO_2e embodied in cellulosic biofuel.

2. The Breakeven Model

We first determine the processor's breakeven value or the maximum amount an ethanol refinery can pay for the last unit of cellulosic feedstock delivered to the biorefinery. This is equivalent to the processor's derived demand for biomass and is denoted as their willingness to pay (WTP). Second, we calculate the biomass supplier's breakeven value or the minimum amount the supplier is willing to accept for the last unit of delivered biomass. This is equivalent to the supplier's marginal cost for the last dry ton of delivered cellulosic material and is denoted as their willingness to accept (WTA). The difference between the processor's WTP and supplier's WTA will determine market feasibility for each feedstock.[7]

Processor WTP

Equation (1) details the processor's WTP, or the derived demand, for one dry ton of cellulosic material delivered to a biorefinery.

[7] The calculated values are long run equilibrium values for the ethanol processors and feedstock suppliers. The purchaser of biomass for ethanol production will be referred to as the "processor" and "supplier" is used to denote the biomass supplier, either a farmer, producer, or intermediate supplier (i.e., consolidator).

$$WTP = \left\{ P_{gas} * E_V + T + V_{BP} + V_O - C_I - C_O \right\} * Y_E \qquad (1)$$

The market price of ethanol (or revenue per unit of output) is calculated as the energy equivalent price of gasoline where P_{gas} denotes the per gallon price of gasoline and E_V denotes the energy equivalent factor of gasoline to ethanol. Based on historical trends, the price of gasoline is calculated as a constant fraction of the price of oil [$P_{gas}= P_{Oil}/29$].[8] Beyond direct ethanol sales, the ethanol processor also receives revenues from tax credits (T), byproduct production (V_{BP}) and octane benefits (V_O) per gallon of processed ethanol. Biorefinery costs are separated into two components: investment costs (C_I) and operating (C_O) costs per gallon. The calculation within brackets in Equation (1) provides the net returns per gallon of ethanol above all non-feedstock costs. To determine the processor's maximum WTP per dry ton of feedstock, a conversion ratio is used for gallons of ethanol produced per dry ton of biomass (Y_E). Therefore, Equation (1) provides the maximum amount the processor can pay for the last dry ton of biomass delivered to the biorefinery and still breakeven.

Model Parameters for Cellulosic Processor WTP

***Price of oil and energy value* (P_{gas} and E_V)**

A critical parameter of the processor's breakeven price is the price of oil. In July 2008, oil escalated to \$145 per barrel but dropped to \$60-\$70 per barrel in later months. Elobeid et al. (2006) assumed a baseline price of \$60 per barrel in their ethanol cost analysis. Rather than simulating or specifying a single price for oil, the difference between the WTP and WTA is calculated for three oil price levels: \$60, \$75 and \$90 per barrel.

***Octane benefits* (V_O)**

Per unit, ethanol provides a lower energy value than gasoline. Currently, the energy equivalent ratio (E_V) for ethanol to gasoline is around 0.667,[9] but technological progress has the potential to increase this value in the future. For this simulation, the energy

[8] The relationship between the price of oil and the price of gasoline is based on historical trends and may be subject to change. [Elobeid et al., 2006]
[9] Elobeid et al., 2006; Tokgoz et al., 2007

equivalent ratio is assumed to have a mean value of 0.67. While it has a lower energy value than pure gasoline, ethanol is an octane enhancer. Blending gasoline with ethanol, even at low levels, will increase the fuel's octane value. For simplicity, the octane enhancement value (V_O) is assumed fixed at $0.10 per gallon.

***Byproduct value* (V_{BP})**

For byproduct value (V_{BP}), we assume excess energy is the only byproduct from the proposed biorefinery. Aden et al. (2002) estimated that cellulosic ethanol production yields excess energy value of approximately $0.14-$0.21, after updating to 2007 energy costs [EIA, 2008]. Without specifying the source of byproduct value, Khanna and Dhungana (2007) used an estimate of around $0.16 per gallon for cellulosic ethanol.[10] Huang et al. (2009) found that switchgrass conversion yields the largest amount of excess electricity followed by corn stover and aspen wood. We assume that switchgrass, *Miscanthus*, prairie grass and wheat straw have a byproduct value of $0.18 per gallon, while corn stover and aspen wood have values of $0.16 and $0.14 per gallon, respectively.

***Incentives and tax credits* (T)**

Growing concern over climate change as well as energy security and independence has resulted in various incentives and mandates for renewable fuels. Tax credits have been the primary financial incentive provided to biofuel producers. To account for potential tax credits for cellulosic ethanol producers, we consider the current tax credit (T) for cellulosic ethanol producers designated by the Food and Energy Security Act of 2007 of $1.01 per gallon and denote this as the "producer's tax credit."

***Conversion ratio* (Y_E)**

The conversion ratio of ethanol from biomass (Y_E) will vary based on feedstock type, conversion process and biorefinery efficiency. Research estimates for the conversion ratio have ranged from as low as 60 gallons per ton to theoretical values as high as 140

[10] Updated to 2007 costs

gallons per ton.[11] Based on these estimates, we assume a conversion ratio with a mean value of 70 gallons per ton as representative of current and near future technology (2009) and a mean of 80 gallons per ton as representative of the long-run conversion ratio (2020).[12]

***Non-feedstock investment costs* (C_I)**

The biorefinery faces two non-feedstock costs: investment costs (C_I) and operating costs (C_O). Investment or capital costs for a biorefinery have been estimated to be four to five times higher than starch-based ethanol plants of similar size [Wright and Brown, 2007]. Operating costs include salaries, overhead, maintenance, insurance, taxes, conversion costs (enzymes), etc. The biorefinery cost estimates used in our model are based on research estimates and numbers provided by Aden et al. (2002), who estimated costs for a biorefinery that processed 2,205 tons of corn stover per day and operated approximately 350 days a year. Aden et al. assumed a conversion ratio of 89.7 gallons of ethanol per ton of stover, resulting in an annual production level of 69.3 million gallons of corn-stover ethanol. Assuming Aden et al.'s feedstock supply of 2,205 tons per day for 350 days per year along with a conversion ratio of 70 gallons per ton results in a 54 million gallon per year cellulosic ethanol refinery for the baseline scenario.[13] Total investment costs for the biorefinery outlined by Aden et al. was $197.4 million. Aden et al. assumed onsite storage, while we place the burden of feedstock storage on the supplier. Therefore, Aden et al.'s estimate for the cost of the concrete storage slab is removed, along with the second set of forklifts used to transport the material from the storage area to the facility. We also reduce the number of yard employees. We assume no down payments and amortize the investment cost over 10 years at 10%. Assuming no down payments, we do not explicitly include depreciation costs. Due to the differences in plant capacities, we

[11] Aden et al., 2002; Atchison and Hettenhaus, 2003; BRDI, 2008; Comis, 2006; Crooks, 2006; Huang et al., 2009; Khanna, 2008; Khanna and Dhungana, 2007; Krissek, 2008; McAloon et al., 2000; Perlack and Turhollow, 2002; Petrolia, 2008; Tiffany et al., 2006;Tokgoz et al., 2007

[12] Ethanol yields vary by feedstock but we were unable to find consistent yield patterns across studies, especially given the lack of commercial cellulosic ethanol plant yield information. Even though woody biomass has a higher lignin yield, some studies also assign a relatively high ethanol yield. With a wide range of estimates for both herbaceous crops and woody biomass and the lack of commercial yield estimates, we chose a conservative approach by assuming the same yield for all feedstock, similar to the ALTF Report (2009). We have estimated results where we allow the ethanol yield to vary by feedstock. These results are available upon request.

[13] A conversion ratio of 80 gallons per ton of feedstock results in a 61.7 million gallon per year biorefinery.

utilize Aden et al.'s per gallon costs rather than annual costs and update to 2007 costs. This results gives a per gallon investment cost around \$0.85 per gallon.

Non-feedstock investment costs **(C_O)**

We separate operating costs into two components: enzyme costs and non-enzyme operating costs. Non-enzyme operating costs, including salaries, maintenance and other conversion costs, are assumed fixed at \$0.36 per gallon. Aden et al. (2002) assumed that enzymes were purchased and set enzyme costs at \$0.10 per gallon.[14] Other (non-updated) published estimates have ranged between \$0.07 and \$0.25 per gallon.[15] Discussions with industry sources indicate that enzyme costs may run between \$0.40 and \$1.00 per gallon given current yields and technology. For simulation, we assume the enzyme cost to have a mean value of \$0.50 per gallon, skewed to allow for cost reductions in the near future.

Supplier's WTA

The biomass supplier's WTA, or marginal cost, for the last unit of feedstock delivered to the biorefinery is detailed in Equation (2).

$$WTA = \left\{ \left(C_{ES} + C_{Opp} \right) / Y_B + C_{HM} + SF + C_{NR} + C_S + DFC + DVC * D \right\} - G \qquad (2)$$

The supplier's WTA for one ton of delivered cellulosic material is equal to the total economic costs the supplier incurs to deliver the last unit of biomass to the biorefinery, minus government incentives received (G) (e.g. tax credits, production subsidies). Depending on the type of biomass feedstock, costs include establishment and seeding (C_{ES}), land/biomass opportunity costs (C_{Opp}), harvest and maintenance (C_{HM}), stumpage fees (SF), nutrient replacement (C_{NR}), biomass storage (C_S), transportation fixed costs (DFC) and variable transportation costs calculated as the variable cost per mile (DVC) multiplied by the average hauling distance to the

[14] Aden et al. (2002) also conducted sensitivity analysis with a mean enzyme cost of \$0.10 per gallon and range of \$0.07 to \$0.20 per gallon.
[15] Aden et al., 2002; Bothast, 2005; Huang et al., 2009; Tiffany et al., 2006

biorefinery (D).[16] Establishment and seeding cost and land/biomass opportunity cost are most commonly reported on a per acre scale. Therefore, the biomass yield per acre (Y_B) is used to convert the per acre costs into per ton costs. Equation (2) provides the minimum amount the supplier can accept for the last dry ton of biomass delivered to the biorefinery and still breakeven.

Model Parameters for Cellulosic Supplier WTA

The supplier's minimum willingness to accept (WTA) for one ton of delivered cellulosic material is equal to the total economic cost the supplier incurs minus government incentives received. Depending on feedstock type, costs include nutrient replacement, harvest and maintenance, transportation, storage, establishment and seeding, chipping fees, stumpage fees, and land/biomass opportunity costs.

***Government incentives* (G)**

For government incentives (G), we account for the dollar for dollar matching payments provided in the Food, Conservation, and Energy Act of 2008 (i.e. 2008 Farm Bill) up to $45 per ton of feedstock for collection, harvest, storage and transportation and denote this as "CHST." Since this payment is a temporary (two-year) program and might not be considered in the supplier's long-run analysis, we conduct the simulation both with and without the CHST payment. The model is flexible enough to account for additional policy incentives, such as the establishment assistance program outlined in the 2008 Farm Bill, which is not analyzed in our simulations since implementation details are not finalized.

***Waste, soil damage, and nutrient replacement* (C_{NR})**

Uncollected cellulosic material adds value to the soil through protection against rain, wind, and radiation, therefore limiting erosion. Erosion results in runoff of fertilizer, nutrients and other agricultural residues into waterways and diminishes soil quality by

[16] The average hauling distance from the farm or storage area to the biorefinery is calculated as a function of the annual biorefinery biomass demand (BD), annual biomass yield (Y_B), and biomass density (B) using the formulation by French (1960) for a circular supply area with a square road grid. The exact equation specification is provided in Section III.

removing organic-matter-rich topsoil [Wilhelm et al., 2004]. Biomass suppliers will incorporate the costs of soil damage and nutrient loss from biomass collection into the minimum price they are willing to accept. Nutrient replacement cost (C_{NR}) varies by feedstock and harvest technique. After adjusting for 2007 costs,[17] estimates for nutrient replacement costs range from \$5 to \$21 per ton.[18] Given these research estimates, nutrient replacement is assumed to have a likeliest value of \$14 per ton, and range of \$4 to \$25 per ton for stover, switchgrass, prairie grass and *Miscanthus*. Nutrient replacement costs for harvested wheat straw is assumed to range between \$0 and \$10 per ton with mean value of \$5 per ton. Nutrient replacement is assumed unnecessary for woody biomass.

***Harvest and maintenance costs* (C_{HM}) *and stumpage fees* (SF)**

Harvest and maintenance cost (C_{HM}) estimates for cellulosic material have varied based on harvest technique and feedstock. Non-custom harvest research estimates range from \$14 to \$84 per ton for corn stover,[19] \$16 to \$58 per ton for switchgrass[20] and \$19 to \$54 per ton for *Miscanthus*,[21] after adjusting for 2007 costs.[22] Estimates for non-specific biomass range between \$15 and \$38 per ton.[23] The USDA Forest Service (2003, 2005) estimated that the price to cut and extract woody biomass to the roadside is between \$35 and \$87 per ton,[24] depending on the type of wood and location. A study by the Biomass Research and Development Institute (BRDI, 2008) estimated the harvest costs of forest biomass (up to roadside) to range between \$40 and \$46 and short-run woody crop harvest to cost around \$17 to \$29 per acre. For this simulation, we assume harvest and maintenance costs to have likeliest values of \$45, \$37, \$47 and \$40 for stover,

[17] Nutrient and Replacement costs were updated using USDA NASS Agricultural Fertilizer Prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[18] Aden et al., 2002; Atchison and Hettenhaus, 2003; Brechbill and Tyner, 2008a; Hoskinson et al., 2007; Huang et al., 2009; Karlen and Birrell (Presentation); Khanna and Dhungana, 2007; Khanna et al., 2008; Perlack and Turhollow, 2003; Perrin et al., 2008; Petrolia, 2008
[19] Aden et al., 2002; Brechbill and Tyner, 2008a; Edwards, 2007; Hess et al., 2007; Haung et al., 2009; Khanna, 2008; McAloon et al., 2000; Perlack (Presentation); Sokhansanj and Turhollow, 2002; Suzuki, 2006
[20] Brechbill and Tyner, 2008a; Duffy, 2007; Huang et al., 2009; Khanna, 2008; Khanna and Dhungana, 2007; Khanna et al., 2008; Kumar and Sokhansanj, 2007; Perrin et al., 2008; Tiffany et al., 2006
[21] Khanna, 2008; Khanna and Dhungana, 2007; Khanna et al., 2008
[22] Harvest and maintenance costs were updated using USDA NASS Agricultural fuel, machinery and labor prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[23] Mapemba et al., 2007; Mapemba et al., 2008
[24] Prices not updated

switchgrass, *Miscanthus* and Aspen wood, respectively. We assume wheat straw and prairie grass to have the same harvest and maintenance cost distribution as switchgrass. In addition to harvest costs, woody biomass suppliers must also pay a stumpage fee (SF) with an assumed mean value of $20 per ton.

***Transportation costs* (DVC), (DFC), and (D)**

Previous research on transportation of biomass has provided two distinct types of cost estimates: (1) total transportation cost; and (2) breakdown of variable and fixed transportation costs. Research estimates for total corn stover transportation costs range between $3 per ton and $32 per ton.[25] Total switchgrass and *Miscanthus* transportation costs have been estimated between $14 and $36 per ton,[26] adjusted to 2007 costs.[27] Woody biomass transportation costs are expected to range between $11 and $22 per dry ton [Summit Ridge Investments, 2007]. Based on the second method, distance variable cost (DVC) estimates range between $0.09 and $0.60 per ton per mile,[28] while distance fixed cost (DFC) estimates range between $4.80 and $9.80 per ton,[29] depending on feedstock type. Our model utilizes the latter method of separating fixed and variable transportation costs.

DFC for corn stover, switchgrass, *Miscanthus*, prairie grass and wheat straw is assumed to range from $5 to $12 per ton with a mean value of $8.50 per ton. Besides loading and unloading costs, woody biomass requires an on-site chipping fee. Therefore, DFC for woody biomass is assumed to have a $20 per ton mean with a range of $6 to $35 per ton. DVC is assumed to follow a skewed distribution to account for future technological progress in transportation of biomass with a likeliest value of $0.35 per ton per mile for stover, switchgrass, *Miscanthus*, prairie grass and wheat straw and $0.50 per ton per mile for woody biomass.

[25] Aden et al., 2002; Atchison and Hettenhaus, 2003; Brechbill and Tyner, 2008a; English et al., 2006; Hess et al., 2007; Mapemba et al., 2008; Perlack (Presentation); Perlack and Turhollow, 2002; Vadas et al., 2008
[26] Duffy, 2007; Brechbill and Tyner, 2008a; Khanna et al., 2008; Kumar and Sokhansanj, 2007; Mapemba et al., 2007; Mapemba et al., 2008; Perrin et al., 2008; Tiffany et al., 2006; Vadas et al., 2008
[27] Transportation costs were updated using USDA NASS Agricultural fuel prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[28] Brechbill and Tyner, 2008a and 2008b; Huang et al., 2009; Kaylen et al., 2000; Kumar et al., 2005; Kumar et al., 2003; Petrolia, 2008; Searcy et al., 2007; USDA Forest Service, 2003 and 2005
[29] Huang et al., 2009; Kumar et al., 2005; Kumar et al., 2003; Petrolia, 2008; Searcy et al, 2007

Expected one-way transportation distance (D) has been evaluated up to 100 miles for woody biomass[30] and between 5 and 75 miles[31] for all other feedstocks. In our model, the average hauling distance is calculated using the formulation by French (1960) for a circular supply area with a square road grid provided in Equation (4) below.[32] Average distance (D) is a function of the annual biorefinery biomass demand (BD), annual biomass yield (Y_B) and biomass density (B).

$$D = 0.4789\sqrt{\frac{BD}{640 * Y_B * B}} \tag{4}$$

Annual biomass demand is assumed to be consistent with the biorefinery outlined for capital and operating cost distributions (771,400 tons per year). Based on available research, biomass density is assumed to follow a normal distribution with a mean value of 0.20 for all feedstocks.[33]

***Storage costs* (C_S)**

Due to the low density of biomass compared to traditional cash crops such as corn and soybeans, biomass storage costs (C_S) can vary greatly depending on the feedstock type, harvest technique and type of storage area. Adjusted for 2007 costs, biomass storage estimates ranged between $2 and $23 per ton.[34, 35] For this simulation, we assume storage costs to follow a skewed distribution for all feedstocks to allow for advancement in storage and densification techniques. The likeliest value for woody biomass storage cost is $12, while corn stover, switchgrass, *Miscanthus,* prairie grass and wheat straw storage costs are assumed to have likeliest value of $11 per ton.

---

[30] USDA Forest Service, 2003 and 2005
[31] Atchison and Hettenhaus, 2003; BRDI, 2008; Brechbill and Tyner, 2008a and 2008b; English et al., 2006; Khanna et al., 2008; Mapemba et al., 2007; Perlack and Turhollow, 2002 and 2003; Taheripour and Tyner, 2008; Tiffany et al., 2006; Vadas et al., 2008
[32] We maintain the authors' simplifying assumption of uniform density.
[33] Brechbill and Tyner, 2008a and 2008b; Huang et al., 2009; McCarl et al., 2000; Perlack and Turhollow, 2002; Petrolia, 2008; Popp and Hogan, 2007
[34] Storage costs were updated using USDA NASS Agricultural building material prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[35] Duffy, 2007; Hess et al., 2007; Huang et al., 2009; Khanna, 2008; Khanna et al., 2008; Mapemba et al., 2008; Petrolia, 2008

***Establishment and seeding costs* (C_{ES})**

Corn stover, wheat straw and woody biomass suppliers are assumed to not incur establishment and seeding costs (C_{ES}), while switchgrass, prairie grass and *Miscanthus* suppliers must be compensated for their establishment and seeding costs. Costs vary by stand length, years to maturity and interest rate. Stand length for switchgrass ranges between 10 and 20 years[36] with full yield maturity by the third year.[37] *Miscanthus* stand length ranges from 20 to 25 years[38] with full maturity between the second and fifth year.[39] Interest rates used for amortization of establishment costs range between 7.5 and 8%.[40] Amortized cost estimates for switchgrass establishment and seeding, adjusted to 2007 costs,[41] are between \$30 and \$200 per acre.[42] *Miscanthus* establishment and seeding cost was estimated to be around \$43 to \$350 per acre.[43] For simulation, switchgrass and *Miscanthus* establishment and seeding costs are assumed to have mean values of \$100 and \$200 per acre, respectively. Prairie grass establishment and seeding costs are assumed to be similar to switchgrass costs.

***Opportunity costs* (C_{Opp})**

To provide a complete economic model, we include the opportunity costs of utilizing biomass for ethanol production. We consider two potential opportunity costs: (1) land opportunity costs, or the forgone returns from land used in biomass production rather than alternative uses and (2) biomass opportunity costs, or forgone returns from selling biomass for alternative use rather than for ethanol production. Examples of land opportunity costs include forgone Conservation Reserve Program (CRP) payments when previously idle CRP land is converted into biomass production (grassland), or forgone net

[36] Brechbill et al., 2008a; Duffy and Nanhou, 2001; Fike et al., 2006a; Khanna, 2008; Khanna et al., 2008; Khanna and Dhungana, 2007; Lewandowski et al., 2003; Popp and Hogan, 2007; Tiffany et al., 2006
[37] Kszos et al., 2002; McLaughlin and Kszos, 2005; Popp and Hogan, 2007; Walsh, 2008
[38] Khanna, 2008; Khanna et al., 2008; Khanna and Dhungana, 2007; Lewandowski et al., 2003
[39] Heaton et al., 2004
[40] Brechbill and Tyner, 2008a and 2008b; Brechbill et al., 2008; Duffy and Nanhou, 2001; Quick, 2003; Sokhansanj and Turhollow, 2002;
[41] Establishment and Seeding costs were updated using USDA NASS Agricultural fuel and seed prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[42] Duffy, 2007; Huang et al., 2009; Khanna et al., 2008; Perrin et al., 2008; Vadas et al., 2008
[43] Huang et al., 2009; Khanna et al., 2008; Lewandowski et al., 2003

returns from cash crop production when a farmer plants perennial grasses instead (cropland). Since land producing corn stover also yields a cash crop, stover suppliers do not face land opportunity costs. Examples of biomass opportunity cost include lost potential net returns from selling biomass for livestock feed, bedding or electric power generation rather than for ethanol production. The total opportunity cost for a given biomass crop will depend on the type of land on which it is produced and alternative uses for the biomass. To account for regional variation in climate and agronomic characteristics, we evaluate the breakeven value for switchgrass in three regions: Midwest (ND, SD, NE, KS, IA, IL, IN), South-Central (OK, TX, AR, LA) and Appalachian (TN, KY, NC, VA, WV, PA). *Miscanthus* is evaluated in the Midwest and Appalachian regions while corn-stover and wheat straw are assumed to be produced on cropland used for production in the Midwest and Pacific Northwest regions (WA, ID, OR), respectively. No regional specific assumptions are made for woody biomass, but implicit carbon prices will be constructed for woody biomass from both farmed trees and forest residue.

Research estimates for corn stover opportunity cost range between \$22 and \$143 per acre.[44] The opportunity cost of switchgrass and *Miscanthus* are significantly higher, with estimates ranging between \$70 and \$230 per acre.[45] Estimates for opportunity cost of non-specific biomass range between \$10 and \$76 per acre,[46] depending on the harvest restrictions under CRP contracts. Opportunity cost of woody biomass is estimated to range between \$0 and \$30 per ton.[47]

In our model, land opportunity cost and biomass opportunity cost are combined into a single parameter (C_{Opp}). Given the research estimates, corn stover opportunity cost is assumed to have a mean value around \$60 per ton. Switchgrass and *Miscanthus* grown in the Midwest are assumed to have a mean opportunity costs of \$150 per acre. Since the opportunity cost for land in the Midwest is highly dependent on the price for cash crops, specifically corn, positive correlation is imposed between the draws for Midwest land opportunity cost and corn stover yield. Switchgrass, prairie grass and *Miscanthus* grown

[44] Khanna and Dhungana, 2007; Edwards, 2007
[45] Brechbill and Tyner, 2008a; Khanna and Dhungana, 2007; Khanna et al., 2008
[46] Khanna et al., 2008; Mapemba et al., 2008
[47] Summit Ridge Investments, 2007; USDA Forest Service, 2003 and 2005

on grassland (Appalachian, South-Central) are assumed to have mean opportunity costs of $100 per acre. Wheat straw opportunity cost is assumed to follow a distribution with likeliest value of $0 per acre with a range of -$10 to $30 per acre. Negative values for the opportunity costs of wheat straw are based on the potential nuisance cost of wheat straw. Occasionally, straw is burned at harvest to avoid grain planting problems during the following crop season.

Biomass yield (Y_B)

The final parameter in the model is biomass yield per acre of land. Biomass yield is variable in the near and distant future due to technological advancements and environmental uncertainties. Corn stover yield per acre will vary based on the amount of corn stover that is removable, which depends on soil quality and other topographical characteristics. Harvested corn stover yield has been estimated between 0.8 to 3.8 tons per acre.[48] Potential switchgrass yields range between 0.89 and 16 tons per acre,[49] depending on region, land quality, switchgrass variety, field versus plot trial studies and harvest technique. On average, *Miscanthus* has significantly higher yield estimates that range between 3.4 and 19.6 tons per acre when both US and EU yield estimates are considered.[50] Estimated U.S. *Miscanthus* yields range between 9 and 18 tons per acre.[51] A wheat straw yield of 1 ton per acre was assumed by the BRDI (2008) study. For woody biomass, Huang et al. (2009) estimated Aspen wood yield of 0.446 dry tons per acre from a densely forested area in Minnesota, while the BRDI (2008) study assumed short-run woody crops yield 5 to 12 tons per acre. The USDA Forest Service (2003,

[48] Atchison and Hettenhaus, 2003; BRDI, 2008; Brechbill and Tyner, 2008a; Duffy and Nanhou, 2001; Edwards, 2007; Huang et al., 2009; Khanna, 2008; Khanna and Dhungana, 2007; Lang, 2002; Perlack and Turhollow, 2002; Prewitt et al., 2007; Quick, 2003; Sokhansanj and Turhollow, 2002; Schechinger and Hettenhaus, 2004; Vadas et al., 2008

[49] Berdahl et al., 2005; Bouton et al., 2002; Brechbill and Tyner, 2008a; BRDI, 2008; Cassida et al., 2005; Comis, 2006; Duffy, 2007; Fike et al., 2006a; Fike et al., 2006b; Gibson and Barnhart, 2007; Heaton et al., 2004a; Huang et al., 2009; Khanna and Dhungana, 2007; Khanna, 2008; Khanna et al., 2008; Kiniry et al., 2005; Kszos et al., 2002; Lewandowski et al., 2003; McLaughlin et al., 2002; McLaughlin and Kszos, 2005; Muir et al., 2001; Nelson et al., 2006; Ocumpaugh et al., 2003; Parrish et al., 2003; Perrin et al., 2008; Popp and Hogan, 2007; Reynolds et al., 2000; Sanderson, 2008; Schmer et al., 2006; Shinners et al., 2006; Taliaferro, 2002; Tiffany et al., 2006; Thomason et al., 2005; Vadas et al., 2008; Vogel et al., 2002; Walsh, 2008

[50] Christian et al., 2008; Clifton-Brown and Lewandowski, 2002; Clifton-Brown et al., 2001; Clifton-Brown et al., 2004; Heaton et al., 2004a and 2004b; Kahle et al., 2001; Khanna, 2008; Khanna and Dhungana, 2007; Khanna et al., 2008; Lewandowski et al., 2000; Lewandowski et al., 2003, Smeets et al., 2009; Stampfl et al., 2007; Vargas et al., 2002

[51] Heaton et al., 2004a and 2004b; Khanna, 2008; Khanna and Dhungana, 2007; Khanna et al., 2008

2005) estimated woody biomass can provide 4.6 to 39 tons per acre, depending on type of wood and location. For this simulation, the mean yield of corn stover is approximately 2 tons per acre. Smooth distributions for switchgrass yields are fit based on the research estimates for regions with sufficient data.[52] Switchgrass grown in the Midwest is found to fit a distribution with a mean value around 4 tons per acre. *Miscanthus* grown in the Midwest is assumed to have a mean value of 6.5 tons per acre.[53] Switchgrass grown in the South-Central region has a higher mean yield of around 5.7 tons per acre. For the regions analyzed, the Appalachian region provides the best climatic conditions for switchgrass and *Miscanthus* with assumed mean yields of 6 and 9 tons per acre, respectively. Prairie grass yield is assumed to follow a distribution with likeliest yield of 3 tons per acre. Wheat straw and aspen wood yields are assumed to be normally distributed with means 1 and 0.5 tons per acre, respectively. Tables summarizing the research estimates used in our analysis are available in Appendix 1.

Clearing the Market for Cellulosic Feedstocks

For a biomass-based ethanol market to exist, the biorefinery and supplier must be able to find a market-clearing price. In other words, the maximum price the biorefinery can pay for the biomass (WTP) must be at least as large as the minimum price the supplier is willing to accept (WTA) for the marginal unit delivered, where both supplier and buyer are at or above their breakeven values. Market existence requires WTP $\geq$ WTA. To evaluate market existence for each feedstock, the difference (Δ) between the WTP and WTA is calculated using equation (3).

$$\begin{aligned}\Delta &= WTP - WTA \\ &= \left\{\left(P_{oil}/29\right)*E_V + T + V_{BP} + V_O - C_I - C_O\right\}*Y_E \\ &\quad -\left\{\left(C_{ES} + C_{Opp}\right)/Y_B + C_{HM} + SF + C_{NR} + C_S + DFC + DVC*D - G\right\} \end{aligned} \tag{3}$$

If the difference value (Δ) is at or above zero for a given feedstock, the biomass supplier and biofuel producer are able to find an agreeable price where they both at least breakeven and a biomass-based ethanol market is feasible. If the difference is negative for a given feedstock, the

[52] Plot trials were evaluated at 80% of their estimated yield.
[53] This is a significantly lower assumed yield than previous research has assumed or simulated. [Khanna and Dhungana, 2007; Khanna et al., 2008; Khanna, 2008; Heaton et al., 2004]

supplier and producer cannot find an agreeable price and the feedstock market cannot be sustained under the assumed market conditions and available technology.

Due to lack of industry data on commercial feedstock production and processing technologies, model breakeven values for the processor and supplier depend on model parameters derived from existing research literature. Since biomass suppliers and cellulosic ethanol processors do not exist on a commercial scale, a literature review on cost and other parameter values recovered estimates that varied significantly due to differences in assumptions and level of cost inclusion. To account for these large variations, we used research estimates to create distributional assumptions that are used in Monte Carlo analyses. Summary tables for the research estimates can be found in Appendix 1, while Appendix 2 provides the distributional assumptions for each parameter.

3. Model Simulation

A commercial-scale cellulosic biorefinery and feedstock supply system do not currently exist, and therefore industry values are not available from existing markets. Industry data are not available on which to establish the biorefinery's derived demand curve for biomass (WTP), nor the biomass supplier's marginal cost curve (WTA). To calculate the processor and supplier breakeven values and to account for the large variability in the research estimates for major parameters within our model, we use Monte Carlo simulations. We use distributional assumptions based on actual research data and industry-based information detailed in the previous section. Consequently, the results of our feasibility analysis will rely on a broad range of published estimates.

Market sustainability (i.e. WTP $\geq$ WTA) is simulated for each (region-specific) feedstock given the distributional assumptions. If a price gap exists between the processor's WTP and supplier's WTA such that a market will not exist under the assumed market conditions, we extend the breakeven analysis to evaluate the carbon price or credit needed to sustain a market for each feedstock. A life-cycle analysis (LCA) is conducted for each feedstock to estimate the carbon savings of the feedstock-specific cellulosic ethanol relative to conventional gasoline. The gap between the WTP and WTA, along with the reduction in carbon emissions from cellulosic ethanol relative to conventional gasoline, quantifies the implicit carbon price or tax needed to sustain a cellulosic ethanol industry. This carbon price can be thought of as either a carbon tax credit provided to the ethanol producer (or feedstock supplier) per ton of cellulosic feedstock refined, or as the market price for carbon credits if processors are allocated marketable carbon credits for biofuel GHG reductions relative to conventional gasoline.

Simulation method

For parameters in Equations (1) and (2), multiple draws are taken from the distributional assumptions of each parameter based on research estimates summarized in Appendix 1. Given the estimated parameter values, the processor's minimum willingness to pay (WTP), supplier's maximum willingness to accept (WTA) and the difference between WTP and WTA (Δ) are calculated. As previously noted, the price of oil is highly variable and a large determinant of ethanol revenue. Therefore, we evaluate the processor's breakeven value and the difference between WTP and WTA at three oil prices: \$60 per barrel (low), \$75 per barrel (baseline) and \$90 per barrel (high). Similarly, technological uncertainty of cellulosic ethanol production provides a wide range of estimates for the ethanol conversion ratio from as low as 60 gallons per ton to theoretical values as high as 140 gallons per ton.[54] Based on these estimates, we assume a conversion ratio with a mean value of 70 gallons per ton[55] as representative of current and near future technology (2009) and a mean of 80 gallons per ton as representative of the long-run conversion ratio (2020).

For government incentives, we consider three alternative policy scenarios. First, we determine the carbon price needed to sustain each feedstock market given no government intervention (i.e. no producer's tax credit or CHST payment). Next, we evaluate how the necessary carbon price changes if producers are provided a production tax credit (i.e. producer's tax credit only). Finally, we determine the carbon price needed to sustain feedstock markets given both the producer's tax credit and supplier CHST payment.[56]

No government intervention

[54] Khanna and Dhungana, 2007; Aden et al., 2002; Petrolia, 2008; Krissek, 2008; Tokgoz et al., 2007; Crooks, 2006; Comis, 2006; McAloon, 2000; Atchison and Hettenhaus, 2003, Perlack and Turhollow, 2002; Khanna, 2008; BRDI, 2008; Tiffany et al., 2006; Huang et al., 2009

[55] See footnote 12 above.

[56] The parameter draws and calculations were repeated one thousand times for each scenario resulting in one thousand values for WTP, WTA, and Δ at each oil price, technology, and policy scenario.

Given the distributional assumptions and Monte Carlo simulation, the estimated mean value of the difference between the processor's WTP and supplier's WTA (Δ) for each feedstock is provided in Table 1 assuming the baseline oil price of $75 per barrel and a 70 gallon per ton conversion ratio. Table 2 provides the corresponding 90% confidence interval for the difference value. Without the current policy incentives (i.e. no producer's credit or CHST payment), no feedstock market exists and the 90% confidence interval is strictly negative for all feedstocks at the baseline oil price and a 70 gallon per ton conversion ratio. Given the difference values for this policy scenario and the carbon emissions savings from cellulosic ethanol relative to conventional transportation fuels, we can determine the carbon price needed to sustain cellulosic ethanol production if carbon credits for GHG reductions were the only policy incentive.

Production tax credit

The second policy scenario we evaluate is the extension of the producer's tax credit of $1.01 for cellulosic biofuel producers. Given the producer's tax credit, $75 per barrel oil and a 70 gallon per ton conversion ratio, wheat straw is the only feasible market without carbon credits or pricing. Relative to other feedstocks, wheat straw grown in the Pacific Northwest has very low opportunity cost and nutrient replacement cost. Wheat straw is also assumed to be supplied from previously established stands, resulting in no establishment or seeding costs. All other feedstock markets are not viable given the estimated mean difference value, but the 90% confidence intervals for the difference between WTP and WTA capture positive values (i.e. market existence) for corn stover, Appalachian and South Central switchgrass, *Miscanthus* from the Appalachian region, prairie grass and woody biomass.

Production tax credit and CHST payment

The third scenario considers market existence given both the producer's tax credit and the CHST payment. When both policy incentives are in place, a feedstock market exists for corn stover, switchgrass grown in the Appalachian region, South-Central switchgrass or *Miscanthus*, wheat straw and woody biomass at the baseline oil price and a 70 gallon per ton conversion ratio. On average, a market does not exist for prairie grass or Switchgrass and *Miscanthus* grown on high opportunity cost Midwest cropland, but a positive difference value (Δ) falls within the 90% confidence interval for each feedstock.

Table 1 – Simulated Mean Difference (Δ) at the Baseline Oil Price (70 gal/ton Conversion)			
	No Credit or Payment	**Credit Only**	**Credit and Payment**
Corn Stover	-$97	-$27	**$19**
Switchgrass (MW)	-$124	-$54	-$10
Switchgrass (App)	-$92	-$22	**$22**
Switchgrass (SC)	-$98	-$26	**$15**
Miscanthus (MW)	-$124	-$52	**-$8**
Miscanthus (App)	-$98	-$27	**$17**
Wheat Straw	-$56	**$14**	**$58**
Prairie Grass	-$121	-$50	-$6
Woody Biomass	-$99	-$28	**$17**

Table 2 – 90% Confidence Interval for the Difference (Δ) at the Baseline Oil Price (70 gal/ton Conversion)			
	No Credit or Payment	**Credit Only**	**Credit and Payment**
Corn Stover	-132, -64	**-63, 13**	**-20, 55**
Switchgrass (MW)	-180, -81	-111, -8	**-62, 34**
Switchgrass (App)	-132, -55	**-66, 16**	**-18, 57**
Switchgrass (SC)	-151, -57	**-84, 16**	**-41, 59**
Miscanthus (MW)	-175, -81	-102, -9	**-60, 34**
Miscanthus (App)	-133, -65	**-65, 9**	**-18, 50**
Wheat Straw	-89, -27	**-18, 45**	**27, 89**
Prairie Grass	-186, -72	**-116, 0**	**-71, 41**
Woody Biomass	-135, -66	**-63, 5**	**-17, 52**

Tables 1 and 2 are based on a conversion rate of 70 gallons of ethanol per ton of feedstock. If technological advancement increases conversion to 80 gallons per ton and oil remains at the baseline price of $75 per barrel, markets still do not exist for any feedstocks with no tax credit or CHST payment, and the 90% confidence intervals remain strictly negative for all feedstocks. With the producer's tax credit and the increased conversion rate, wheat straw is still the only feedstock market in existence given the mean simulation results but the 90% confidence intervals for all feedstocks now include values within the positive range (i.e. market existence). Given the increased conversion rate and both the producer's tax credit and CHST supplier payment, all feedstock markets are feasible at the mean results from the simulation.

The next section summarizes select simulation results based on the distributional assumptions. Appendix 2 provides complete distributional assumptions including visual depictions for each parameter assumption. Additional simulation results for alternative policy options, conversion ratios and oil price scenarios are provided in Appendix 3. The model and simulation program are flexible and simulation results based on alternative assumptions are available upon request.

Simulation results and analysis

Biofuels have the potential to reduce carbon emissions relative to conventional transportation fuels (i.e. gasoline and diesel), providing additional benefits beyond utilization of a renewable feedstock. To estimate emission impacts from advanced fuels and vehicle technology, we use GREET 1.8, an Excel-based program developed by the Center for Transportation Research at Argonne National Laboratory. For our analysis, GREET provides the total greenhouse gas (GHG) emissions per mile from both conventional gasoline and cellulosic ethanol. The change in emissions from ethanol relative to gasoline along with ethanol yield (gallons per ton) and fuel efficiency (miles per gallon) provide the necessary information to determine GHG savings per ton of feedstock. To provide a cohesive analysis, we adjust the default assumptions in GREET to fit our model assumptions for both ethanol yield and average hauling distance from the storage area to the biorefinery. Since the timing of a cellulosic ethanol market is indeterminate, emissions impacts are estimated under four scenarios: (i) 2009 technology with an ethanol fuel efficiency of 23 MPG; (ii) 2009 technology at the default fuel efficiency provided by GREET for fuel-celled passenger vehicles of 32 MPG; (iii) 2020 technology with an ethanol fuel efficiency of 32 MPG; and (iv) 2020 technology at the default fuel efficiency of 41.4 MPG for fuel-celled passenger vehicles. For conventional gasoline, we use the default parameters for fuel efficiency provided by GREET of 23 MPG for 2009 passenger vehicles and 25.4 MPG for 2020 passenger vehicles. Table 3 details the assumptions utilized in the GREET fuel-cycle emissions analysis.

Table 3. Assumptions for GREET Fuel-Cycle Emissions Analysis

	Feedstock	Conversion Rate	Distance[57]	Year	Fuel Efficiency

[57] Distance is the average hauling distance from the storage area to the biorefinery calculated using equation (4) and parameter assumptions provided in Appendix 2.

		(gallons/ton)	(miles)		(MPG)
Conventional Gasoline				2009 2020	23.12 25.4
Corn Stover	Corn Stover	70 80	25	2009 2020	23.12 and 32 41.4 and 32
Switchgrass (MW)	Herbaceous Energy Crops	70 80	17	2009 2020	23.12 and 32 41.4 and 32
Switchgrass (App)	Herbaceous Energy Crops	70 80	14	2009 2020	23.12 and 32 41.4 and 32
Switchgrass (SC)	Herbaceous Energy Crops	70 80	15	2009 2020	23.12 and 32 41.4 and 32
Miscanthus (MW)	Herbaceous Energy Crops	70 80	14	2009 2020	23.12 and 32 41.4 and 32
Miscanthus (App)	Herbaceous Energy Crops	70 80	13	2009 2020	23.12 and 32 41.4 and 32
Wheat Straw	Herbaceous Energy Crops	70 80	37	2009 2020	23.12 and 32 41.4 and 32
Prairie Grass	Herbaceous Energy Crops	70 80	19	2009 2020	23.12 and 32 41.4 and 32
Farmed Trees	Farmed Trees	70 80	50	2009 2020	23.12 and 32 41.4 and 32
Forest Residue	Forest Residue	70 80	50	2009 2020	23.12 and 32 41.4 and 32

Given our model assumptions, the percentage of GHG emissions savings from cellulosic ethanol relative to conventional gasoline per mile for each feedstock are provided in Table 4. Per mile emissions savings are converted into savings per ton of feedstock, provided in Table 5, using fuel efficiency and ethanol conversion rate assumptions. Corn stover provides 89% to 94% savings, depending on technological year and fuel efficiency, which corresponds to 0.85 - 1.66 tons CO_2e savings per ton of stover. Switchgrass-, Miscanthus-, wheat straw- and prairie grass-based ethanol provide 84% to 92% GHG savings per mile or 0.79 - 1.61 tons CO_2e savings per ton of feedstock compared to conventional gasoline. GREET allows estimation of two types of woody biomass feedstock: farmed trees and forest residues. Forest residues provide relative savings of 88% to 96% of CO_2e per mile, while farmed trees provide substantially higher savings of 108% to 115%.

Table 4. GHG Emissions Changes Relative to Gasoline Vehicle Fueled with Conventional Gasoline (CG) (grams of CO2e/mile)

	2009 (23 MPG)	2009 (32 MPG)	2020 (32 MPG)	2020 (41 MPG)
Corn Stover	-89%	-92%	-93%	-94%
Switchgrass (MW)	-84%	-88%	-89%	-91%

Switchgrass (App)	-84%	-88%	-89%	-92%
Switchgrass (SC)	-84%	-88%	-89%	-92%
Miscanthus (MW)	-84%	-88%	-89%	-92%
Miscanthus (App)	-84%	-88%	-89%	-92%
Wheat Straw	-84%	-88%	-88%	-91%
Prairie Grass	-84%	-88%	-89%	-91%
Farmed Trees[58]	-115%	-111%	-111%	-108%
Forest Residue	-88%	-91%	-95%	-96%

Table 5. GHG Savings by Feedstock (tons CO2e/ton feedstock)

	2009 (23 MPG)	**2009 (32 MPG)**	**2020 (32 MPG)**	**2020 (41 MPG)**
Corn Stover	0.85	1.21	1.26	1.66
Switchgrass (MW)	0.80	1.16	1.21	1.61
Switchgrass (App)	0.80	1.16	1.21	1.61
Switchgrass (SC)	0.80	1.16	1.21	1.61
Miscanthus (MW)	0.80	1.16	1.21	1.61
Miscanthus (App)	0.80	1.16	1.21	1.61
Wheat Straw	0.79	1.15	1.20	1.60
Prairie Grass	0.80	1.16	1.21	1.61
Farmed Trees	1.09	1.51	1.51	1.91
Forest Residue	0.83	1.20	1.30	1.70

Using the difference between the processor's WTP and supplier's WTA coupled with the GHG savings per ton of feedstock, we derive the minimum carbon credit or price necessary to sustain a cellulosic ethanol market for each feedstock. The carbon credit or price needed for a feedstock market to exist is derived by dividing the difference between the WTP and WTA (Table 1 and Appendix Table 3-7) by the carbon savings per ton of feedstock (Table 5). If the difference between WTP and WTA is positive for any feedstock without a carbon credit, then the feedstock market exists and any additional credit will be profit to either the supplier or processor.

The resulting implicit carbon price depends on all values and assumptions used to derive the WTA, WTP and GHG savings per ton of feedstock including policy incentives, oil price, regional land quality and climate variation, technology and parameter variability. Figure 1 provides a visual depiction of the carbon credit or price necessary to sustain a market for each

58 Though initially counter-intuitive, the GHG savings in Table 4 for farmed wood are lower in the higher fuel efficiency scenario since the values presented are on a per mile basis. For farmed wood, the greatest savings in CO_2e emissions comes from the feedstock production stage. Farmed wood is the only case where fuel savings per mile is lower for higher fuel efficiency due to the large relative savings during the farming stage. In this case, the savings are spread out over more miles when calculated on a per mile basis since emissions reduction per gallon is composed of two components: (fuel savings per mile) * (miles driven per gallon). As is shown in Table 5, when this is converted into savings per ton of feedstock, the higher fuel efficiency scenario does provide more savings per ton of feedstock.

feedstock for three potential policy scenarios assuming the baseline oil price, a conversion rate of 70 gallons per ton, 23 MPG fuel efficiency for fuel-celled and conventional gasoline vehicles, and 2009 technology. The values in Figure 1 are derived using the mean of the simulation results. Since the carbon price is derived from parameter values with fitted distributions rather than point estimates, the simulation provides a distribution for the implicit carbon price for each scenario. Figure 2 presents the distribution of simulation results for the carbon price needed to sustain a corn stover market given the producer's tax credit and the same technological assumptions used to derive Figure 1.

Figure 1 - Carbon Price Needed for Feedstock Market by Policy Incentive
($75/barrel oil, 23 mpg, 2009)

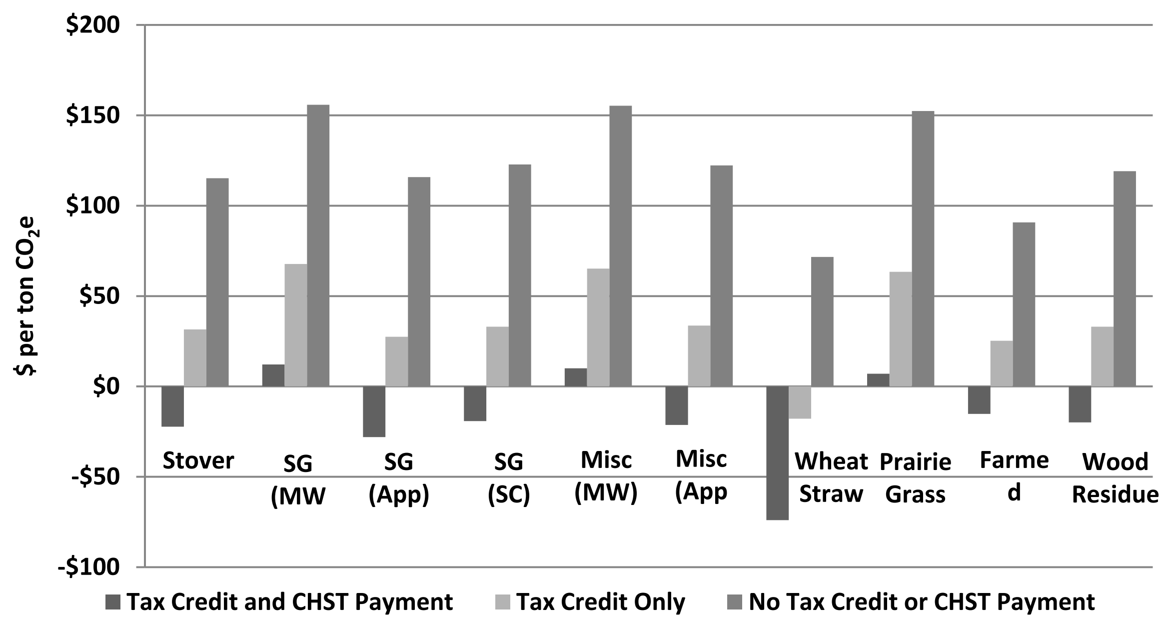
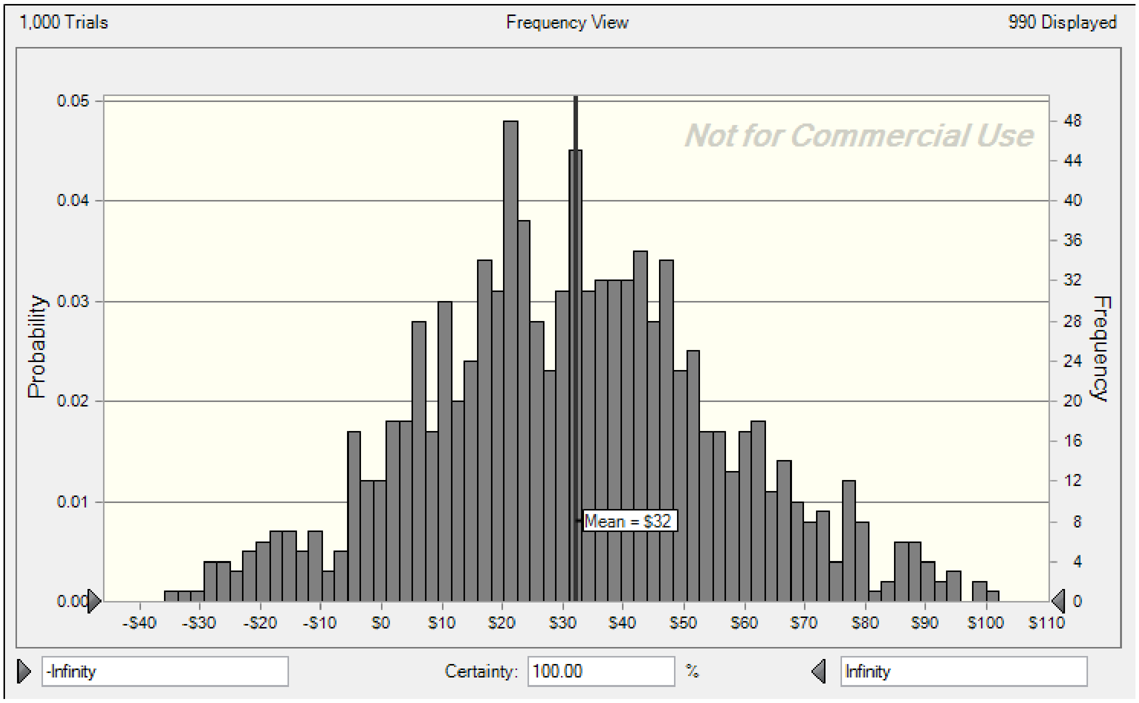


Figure 2 – Simulation for the Carbon Price Needed to Sustain a Stover Market Producer's Credit Only
($75/barrel oil, 23 MPG, 2009)



Sensitivity of Implicit Carbon Price

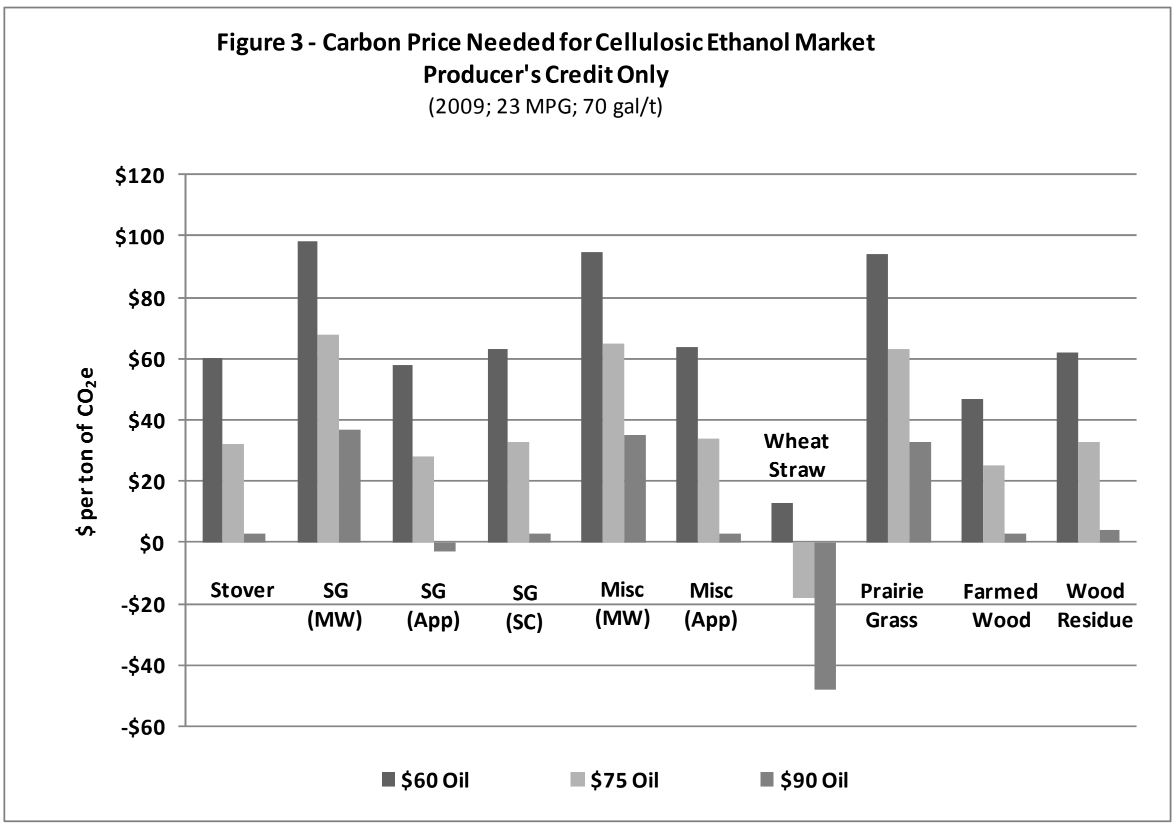
To demonstrate the sensitivity of our results to model assumptions, we present select sensitivity results below. For consistency, we provide sensitivity to a "baseline" scenario within the text and provide sensitivity results for other scenarios in Appendix 3. The baseline scenario consists of an oil price of $75 per barrel, 70 gallon per ton conversion rate, 23 MPG fuel efficiency for fuel-celled vehicles and 2009 technology.[59]

Oil Price

Since the ethanol price is assumed to equal the energy equivalent price of gasoline, and the price of gasoline is driven by the price of oil, the refiner's revenue from ethanol production is highly dependent on the price of oil. Figure 3 shows the sensitivity of the carbon credit needed for feedstock markets to exist at the three oil price levels. At the high oil price ($90 per barrel), only wheat straw and Appalachian switchgrass markets exist without carbon credits for relative GHG savings. The remaining feedstocks need a carbon price of $3 per ton of CO_2e (farmed wood) to $37 per ton of CO_2e (Midwest

[59] The sensitivity of the carbon price to policy incentives was discussed in the previous section and depicted in Figure 1 and therefore will not be covered in this section.

switchgrass) for market existence. At the baseline oil price, the only market without carbon pricing is a wheat straw market, while the carbon price to sustain markets for the remaining feedstocks increases to $25 per ton of CO_2e (farmed trees) to $68 per ton of CO_2e (Midwest switchgrass). Finally, when oil price drops to $60 per barrel, lowering the refiner's revenue from ethanol production and their ability to pay for feedstock, all feedstocks need a positive carbon price for relative GHG savings for market existence. The carbon price ranges from $13 per ton CO_2e for wheat straw to $98 per ton CO_2e for Midwest switchgrass. Therefore, within our model, the carbon price needed to sustain feedstock markets is highly sensitive to the price of oil. The results are similar for non-baseline scenarios, available in Appendix Table 3-9.



Regional Differences

To account for regional variation in climate and agronomic characteristics, the breakeven value for switchgrass suppliers was evaluated for three regions: Midwest (MW), South-Central (SC) and Appalachian (App). *Miscanthus* was also evaluated in the Midwest and

Appalachian regions. Figures 1 and 3 provide some indication of the sensitivity of the carbon price to regional differences. Figure 4 provides a direct comparison of the carbon price needed to sustain a switchgrass market between the three regions. Figure 5 provides a similar comparison between the two regions for *Miscanthus*. Switchgrass and *Miscanthus* grown in the Midwest require a significantly higher carbon price due to alternative land use value (cash crops) and lower biomass yields in the Midwest relative to the alternative region(s) evaluated. The carbon price needed for a switchgrass feedstock market to exist in the Midwest is over double the price needed for a switchgrass market in the South-Central or Appalachian regions under the assumed market conditions. Regional characteristics including land quality and alternative land use play an important role in the viability of feedstocks for ethanol production.

Figure 4 - Simulation for the Carbon Price Needed to Sustain a Switchgrass Market by Region
Producer's Credit Only
($75/barrel oil, 23 MPG, 2009)

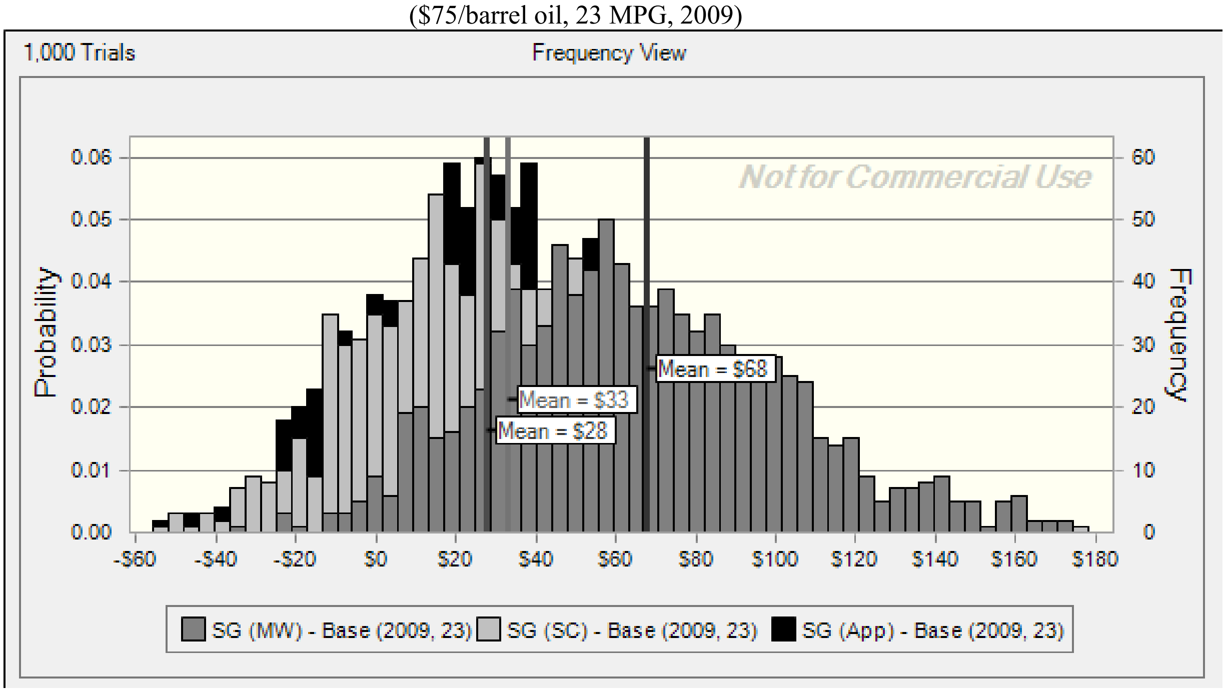
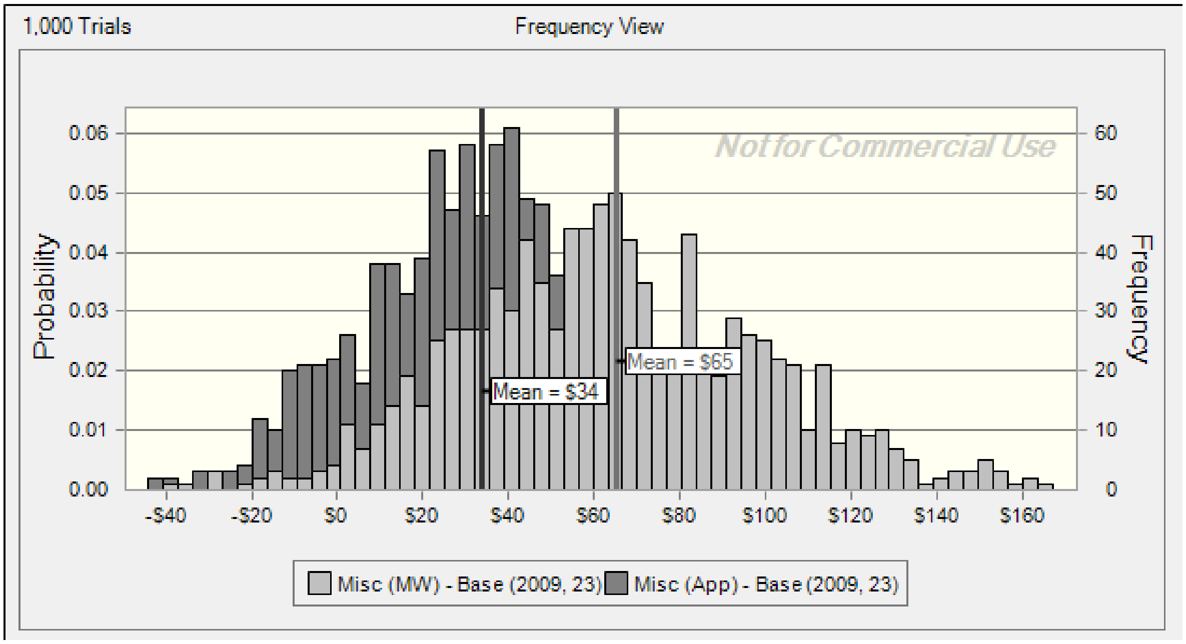


Figure 5 - Simulation for the Carbon Price Needed to Sustain a *Miscanthus* Market by Region
Producer's Credit Only
($75/barrel oil, 23 MPG, 2009)

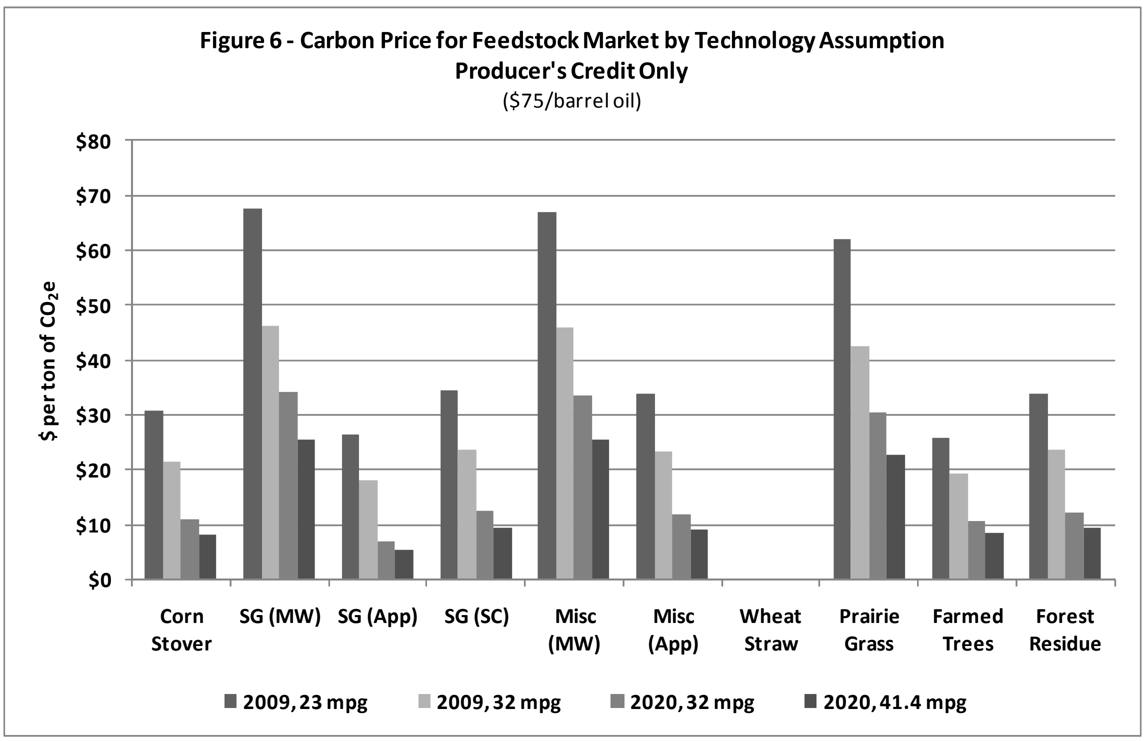


Improved Biomass Conversion and Driving Efficiency

Technological advancement has the potential to significantly lower biomass production and biofuel processing costs. We evaluate the sensitivity of the carbon price to fuel efficiency and then test the sensitivity of the results to improved plant technology including ethanol to biomass conversion ratio. In all scenarios, a conversion ratio of 70 gallons of cellulosic ethanol per ton of feedstock is assumed to be representative of current and near term technology (2009), while we assume technological advancement to increase this conversion rate to 80 gallons per ton by 2020. To evaluate the sensitivity of our results to improved fuel efficiency, we evaluate the carbon price needed to sustain each feedstock market for four scenarios: (i) 2009 biorefinery technology with an ethanol fuel efficiency of 23 MPG; (ii) 2009 biorefinery technology at the default fuel efficiency provided by GREET for fuel-celled passenger vehicles of 32 MPG; (iii) 2020 biorefinery technology with an ethanol fuel efficiency of 32 MPG; and (iv) 2020 biorefinery technology at the default fuel efficiency of 41.4 MPG for fuel-celled passenger vehicles.[60] For conventional gasoline, we use the default parameters for fuel efficiency provided by GREET of 23 MPG for 2009 passenger vehicles and 25.4 MPG for 2020 passenger vehicles. Figure 6 provides the carbon price needed to support each feedstock

[60] Fuel efficiency is based on a fuel-cell vehicle operating on cellulosic ethanol.

market for the four fuel-efficiency and plant technology scenarios. Since a wheat straw market is sustainable in all scenarios without carbon credits/payments, the carbon price needed for market existence is zero. Increasing fuel efficiency for 2009 fuel-celled vehicles (FCV) from 23 MPG to 32 MPG, while maintaining plant technology and holding fuel efficiency for conventional gasoline vehicles (CV) constant at 23 MPG, decreases the carbon price needed for market existence between \$6 and \$21 per ton of CO_2e.[61] Similarly, increasing fuel efficiency for 2020 fuel-celled vehicles from 32 MPG to 41.4 MPG, while maintaining plant technology and holding fuel efficiency for conventional gasoline vehicles constant at 25.4 MPG, decreases the carbon price by \$2 to \$8 per ton of CO_2e.[62]



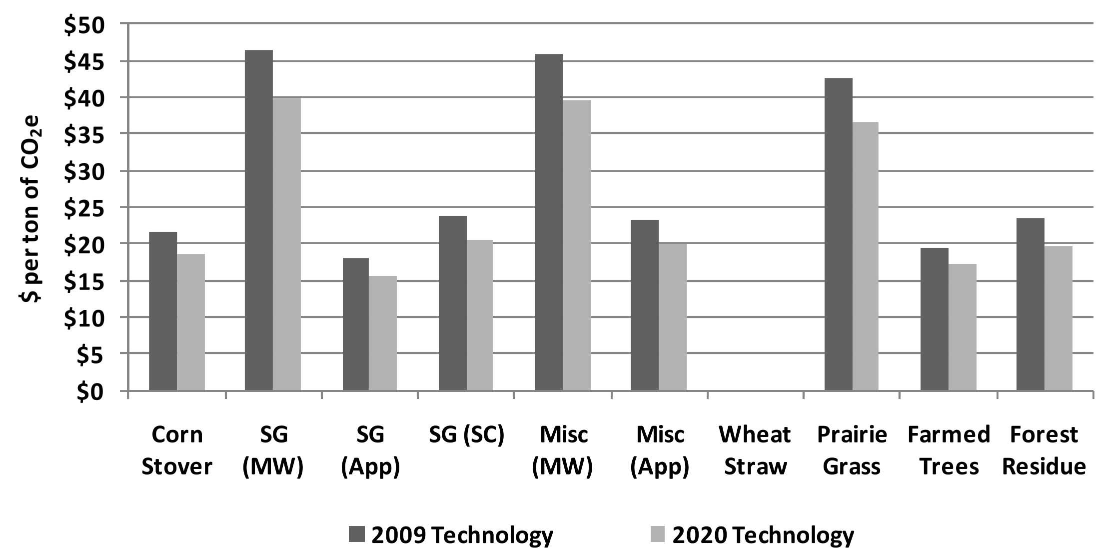
* 70 gallons per ton conversion assumed for 2009 technology
* 80 gallons per ton conversion assumed for 2020 technology

To test the sensitivity of our results to plant technology, including improved biomass to ethanol conversion, we compare the carbon price needed to sustain feedstock markets assuming a 2009 biorefinery to the carbon price needed to sustain feedstock markets

[61] Price differences are from a comparison of scenario (i) to scenario (ii).
[62] Price differences are from a comparison of scenario (iii) to scenario (iv).

assuming a 2020 biorefinery while holding fuel efficiency constant. Therefore, we derive the carbon price needed to sustain feedstock markets for a 2020 biorefinery with an 80 gallon per ton conversion ratio while holding fuel efficiency constant at the 2009 GREET default fuel efficiency values of 32 MPG for fuel-celled vehicles and 23 MPG for conventional gasoline vehicles. We compare results from this scenario to results from a 2009 plant with equivalent fuel efficiency (i.e. scenario (ii) outlined above) to evaluate the change in carbon pricing from increased plant technology. Figure 7 presents results for these two technology scenarios. Depending on feedstock type, the increase in plant technology reduces the carbon price needed to sustain feedstock markets between \$2 and \$6 per ton of CO_2e. From the sensitivity of our results to both fuel efficiency and plant technology, our model provides evidence that technological advancement will play a key role in the existence of a cellulosic ethanol industry.

Figure 7 - Carbon Price for Feedstock Market by Technology Assumption
Producer's Credit Only
(\$75/barrel oil; 23 MPG CV; 32 MPG FCV)



* 70 gallons per ton conversion assumed for 2009 technology
* 80 gallons per ton conversion assumed for 2020 technology

Parameter Variability

Due to the high variability within current published research on cellulosic ethanol production costs and technology, we fit distributions for the model parameters rather than impose point estimates. To test sensitivity of our results to our distributional assumptions, we construct tornado charts for our baseline scenario. A tornado chart provides the sensitivity of the derived carbon price to each parameter distribution. Each distributional assumption is tested independently to analyze the impact on the target value. The chart forms a tornado-like image where the parameter impacts are displayed by declining impact value (downside to upside range). Figure 8 is a tornado chart for the carbon price needed to sustain a switchgrass market in the Appalachian region in our baseline scenario. The carbon price is most sensitive to biomass yield and biorefinery capital costs. Appendix Tables 4-12 to 4-21 provide tornado charts for the remaining feedstocks. Switchgrass, *Miscanthus* and prairie grass are most sensitive to biomass yield and capital cost, while stover is most sensitive to capital cost and land/biomass opportunity cost. Woody biomass is most sensitive to biorefinery capital costs and biomass harvest cost.

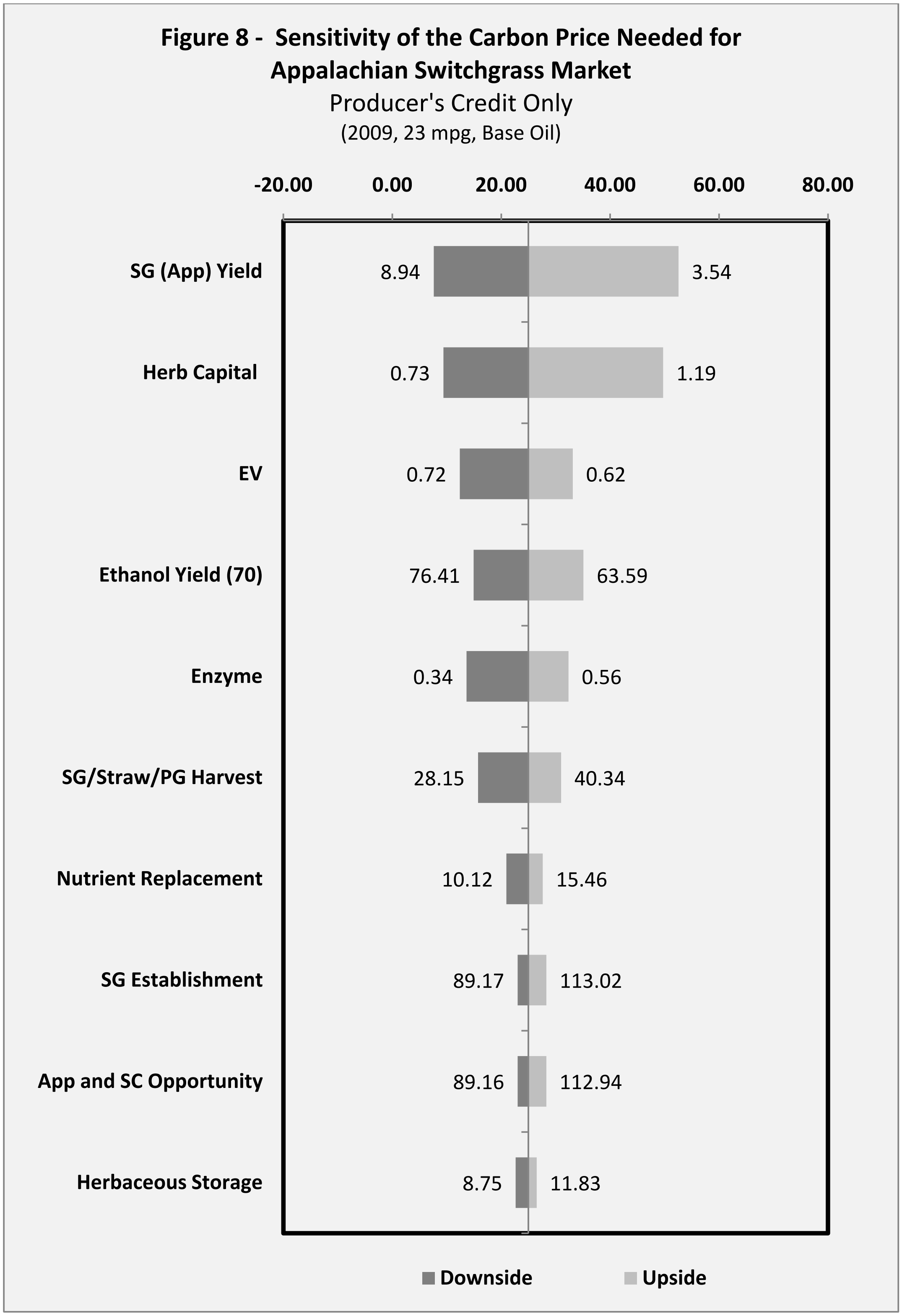


Figure 8 - Sensitivity of the Carbon Price Needed for Appalachian Switchgrass Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
-20.00
0.00
20.00
40.00
60.00
80.00
SG (App) Yield
8.94
3.54
Herb Capital
0.73
1.19
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
SG/Straw/PG Harvest
28.15
40.34
Nutrient Replacement
10.12
15.46
SG Establishment
89.17
113.02
App and SC Opportunity
89.16
112.94
Herbaceous Storage
8.75
11.83
Downside
Upside

4. Summary and Conclusions

We have constructed a long run equilibrium model to determine the feasibility of a cellulosic ethanol market for six potential feedstocks: corn-stover, switchgrass, Miscanthus, wheat straw, prairie grass, forest residue and farmed woody biomass (aspen wood). Feasibility is based on the difference between the processor's maximum willingness to pay (WTP) and supplier's minimum willingness to accept (WTA) for biomass delivered to the biorefinery. The basic economic modeling framework consists of establishing parameters for and estimating processors' WTP or derived demand curves for the last ton of biomass feedstock and suppliers' WTA or MC curves for supplying the last ton of biomass feedstock to the plant. Alternatively, these equations can be viewed as long run equilibrium or breakeven equations in a competitive biomass feedstock market. Model parameters are developed from cost estimates drawn from the literature and updated to 2007 values, industry expertise and unpublished research. These estimates are used to establish distributional assumptions. Where sufficient data exists, we use a Monte Carlo simulation approach to estimate mean parameter values and the distribution of outcomes; if not, we specify a distribution based on available observations.

Given the baseline assumptions, several cellulosic feedstock alternatives exist assuming the biofuel tax credit provided by the EISA (2007) and the CHST biomass producer incentives provided by the FCEA (2008) were long-run policies. In the absence of the CHST subsidies, only wheat straw in the PNW would have the potential to develop a market under baseline conditions. Additionally, given the transportation economies involved in delivering wheat straw, there is likely only sufficient wheat straw to economically supply one 50 million gallon/year plant in the PNW. In the absence of both the cellulosic ethanol tax credit of $1.01/gallon and CHST payment, not even a market for wheat straw would survive at $75/barrel crude oil.

We estimate GHG savings using LCA for cellulosic feedstock alternatives and calculated the implicit carbon prices or credits that would be required to sustain a market for cellulosic feedstock alternatives with and without cellulosic ethanol tax credits and biomass CHST incentives. Again, several of the feedstock alternatives would exist with no carbon pricing if both incentives were available; but in the absence of government incentives for cellulosic ethanol, the carbon price would have to range from $75 to over $150/ton of carbon equivalent to sustain a market for cellulosic feedstock alternatives. Industry sources anticipate that with a high carbon price, cellulosic feedstock will be bid away by power plants to be co-fired with coal, a higher-valued use, to generate electricity.

The RFS.2 mandate can be considered in this analytical framework as well. We first calculate the difference between the WTP and WTA, or the $/biomass ton, with or without other subsidies, which provides an approximation of the added cost that the feedstock processor has to incur to obtain sufficient feedstock to meet the mandated blending requirements. That cost/ton can easily be converted to cost/gallon of cellulosic ethanol to determine added costs passed downstream in the liquid transportation system and ultimately to consumers. Further, the price or cost of Renewable Identification Numbers (RINs) for cellulosic ethanol should closely reflect these added feedstock costs assuming that biomass purchases are in lieu of buying RINs.

The analytical framework developed here is: 1) a comprehensive accounting of all costs, including opportunity costs, that typically enter feedstock suppliers' and processors' decision calculus in making long run breakeven decisions; 2) straightforward, easily manipulated and amenable to location specific analysis; and 3) capable of considering different scenarios, incentive policies and oil price assumptions. To keep the model simple, we have not attempted to endogenize the ramifications of energy price changes on everything from production to transportation costs; in that sense, the model is in an engineering framework.

Despite accounting for the large variation in research estimates in our economic accounting model, there are several other issues this analysis does not address. Transaction costs associated with contractual issues between the supplier and processor are not addressed in our analysis, including risk premiums or minimum farmer profits necessary to induce investment and commitment to supply biomass. Closely related to transaction costs are market power issues, where one player holds more negotiation power. Biomass suppliers may hold the initial power with alternative land use opportunities, but after establishment and seeding, the biorefinery may gain some negotiation power if the farmer has committed to a specific biomass (10 to 20 year stand). Therefore, it is likely that long-term contracts will occur between suppliers and processors.

Advancement in technology may lead to logistical and conversion changes. Custom harvesting operations or intermediate handlers (consolidators) may harvest, store and transport the biomass. Biorefineries may also become multi-feedstock facilities. Ability to convert multiple feedstocks would increase local feedstock supply and decrease transportation distance but may also create logistical issues. Demand and supply of ethanol will also have both local and national labor impacts, which may affect input costs. Finally, model variables were assumed to vary only by feedstock and select regional differences. Additional regional differences may also affect feedstock costs, investment costs, etc. We plan to address these issues in future extensions of this analysis.

REFERENCES

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas. June 2002. "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover." *NREL*: Technical Report. NREL/TP-510-32438.

America's Energy Future Panel on Alternative Liquid Transportation Fuel (ALTF). 2009. "Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts." National Academy of Sciences, National Academy of Engineering and National Research Council. The National Academies Press.

Atchison, J. and J. Hettenhaus. March 2003. "Innovative Methods for Corn Stover Collecting, Handling, Storing and Transporting." National Renewable Energy Laboratory. NREL/SR-510-33893. http://www.nrel.gov/docs/fy04osti/33893.pdf

Berdahl, J., A. Frank, J. Krupinsky, P. Carr, J. Hanson, and H. Johnson. 2005. "Biomass Yield, Phenology, and Survival of Diverse Switchgrass Cultivars and Experimental Strains in Western North Dakota." *Agronomy Journal* **97**:549-555.

Biomass Research and Development Institute (BRDI). 2008. "Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications, and the Role of Research." Biomass Research and Development Board.

Bothast, R. J. Dec. 2005. "Cellulosic Ethanol Technology Assessment." Presentation notes.

Brechbill, S. and W. Tyner. April 2008a. "The Economics of Biomass Collection, Transportation, and Supply to Indiana Cellulosic and Electric Utility Facilities." Department of Agricultural Economics, Purdue University. Working Paper #08-03.

Brechbill, S. and W. Tyner. 2008b. "The Economics of Renewable Energy: Corn Stover and Switchgrass." Department of Agricultural Economics, Purdue University. Purdue Extension ID-404-W.

Duffy, Mike. December 2007. "Estimated Costs for Production, Storage, and Transportation of Switchgrass." *Iowa State University – University Extension.* File: Economics 1-8.

Cassida, K., J. Muir, A. Hussey, J. Read, B. Venuto, and W. Ocumpaugh. 2005. "Biomass Yield and Stand Characteristics of Switchgrass in South Central U.S. Environments." *Crop Science* **45**:673-681.

Christian D., A. Riche, and N. Yates. 2008. "Growth, Yield and Mineral Content of *Miscanthus x Giganteus* Grown as a Biofuel for 14 Successful Harvests." *Industrial Crops and Products*. doi:10.1016/j.indcrop.2008.02.009.

Clifton-Brown, J. and I. Lewandowski. 2002. “Screening *Miscanthus* Genotypes in Field Trials to Optimal Biomass Yield and Quality in Southern Germany.” *European Journal of Agronomy* **16**:97-110.

Clifton-Brown, J., I. Lewandowski, B. Andersson, G. Basch, D. Christian, J. Kjeldsen, U. Jorgensen, J. Mortensen, A. Riche, K. Schwarz, K. Tayebi, and F. Teixeira. 2001. “Performance of 15 *Miscanthus* Genotypes at Five Sites in Europe.” *Agronomy Journal* **93**:1013-1019.

Clifton-Brown, J., P. Stampfl., and M. Jones. 2004. “*Miscanthus* Biomass Production for Energy in Europe and its Potential Contribution to Decreasing Fossil Fuel Carbon Emissions.” *Global Change Biology* **10**:509-518.

Comis, D. July 2006. “Switching to Switchgrass makes Sense.” ARS. *Agriculture Research.* Pg 19.

Crooks, A. Sep/Oct 2006. “From Grass to Gas: On the Road to Energy Independence, How soon wills Cellulosic Ethanol be a Factor?” *Rural Cooperatives* (Ethanol Issue), pp. 16-18.

Duffy, M. and V. Nanhou. 2002. “Costs of Producing Switchgrass for Biomass in Southern Iowa.” *Trends in New Crops and New Uses*, ASHA Press, Alexandria, VA, pp. 267-275.

Edwards, William. December 2007. “Estimating a Value for Corn Stover.” *Iowa State University – University Extension.* File A1-70.

Eidman, Vernon. November 2007. “Ethanol Economics of Dry Mill Plants.” Corn-Based Ethanol in Illinois and the U.S.: A Report from the Department of Agricultural and Consumer Economics. Chapter 3. University of Illinois.

Elobeid, A., S. Tokgoz, D.J. Hayes, B.A. Babcock, and C.E. Hart. Nov 2006. “The Long-Run Impact of Corn-Based Ethanol on the Grain, Oilseed, and Livestock Sectors: A Preliminary Assessment.” *Center for Agricultural and Rural Development.* Briefing Paper: 06-BP 49.

Energy Information Agency. “Average Retail Price of Electricity to Ultimate Customers Total End-Use Sector.” Retrieved September 23, 2008. http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html

English, B.C., D.G. De La Torre Ugarte, K. Jensen, C. Hellwinckel, J. Menard, B. Wilson, R. Roberts, and M. Walsh. Nov 2006. “25% Renewable Energy for the United States by 2025: Agricultural and Economic Impacts.” University of Tennessee.

Fike, J., D. Parrish, D. Wolf, J. Balasko, J. Green Jr., M. Rasnake, J. Reynolds. 2006a. “Long-term Yield Potential of Switchgrass-for-Biofuel Systems.” *Biomass and Bioenergy* **30**:198-206.

Fike, J., D. Parrish, D. Wolf, J. Balasko, J. Green Jr., M. Rasnake, J. Reynolds. 2006b. "Switchgrass Production for the Upper Southeastern USA: Influence of Cultivar and Cutting Frequency on Biomass Yields." *Biomass and Bioenergy* **30**:207-213.

French, B. 1960. Some Considerations in Estimating Assembly Cost Functions for Agricultural Processing Operations. *Journal of Farm Economics* **62**:767-778.

Gibson, L. and S. Barnhart. 2007. "Switchgrass." Iowa State University, University Extension. Department of Agronomy. Crop, Soil, and Environmental Sciences. http://www.extension.iastate.edu/publications/ag200.pdf

Heaton, E., T. Voight, and S. P. Long. 2004a. "A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. "*Biomass and Bioenergy* **27**:21-30.

Heaton, E. A., J. Clifton-Brown, T. B. Voight, M. B. Jones, and S. P. Long. 2004b. "*Miscanthus* for renewable energy generation: European Union experience and projections for Illinois." *Mitigation and Adaptation Strategies for Global Change* **9**:433-451.

Hess, J.R., C.T. Wright, and K.L. Kenney. 2007. "Cellulosic Biomass Feedstocks and Logistics for Ethanol Production." *Biomass, Bioproducts and Biorefining* **1**:181-190.

Hoskinson, R.L., D.L. Karlen, S.J. Birrell, C.W. Radtke, and W.W. Wilhelm. Feb-March 2007. "Engineering, Nutrient Removal, and Feedstock Conversion Evaluations of Four Corn Stover Harvest Scenarios." *Biomass and Bioenery* **31**:126-136.

Huang, H., S. Ramaswamy, W. Al-Dajani, U. Tschirner, and R. Cairncross. 2009. "Effect of Biomass Species and Plant Size on Cellulosic Ethanol: A Comparative Process and Economic Analysis." *Biomass and Bioenergy* **33**: 234-246.

Kahle, P., S. Beuch, B. Boelcke, P. Leinweber, H. Schulten. 2001. "Cropping of *Miscanthus* in Central Europe: Biomass Production and influence on Nutrients and Soil Organic Matter." *European Journal of Agronomy* **15**:171-184.

Karlen, D.L. and S.J. Birrell. "Crop Residue – What's It Worth?" *USDA & Iowa State University*. Presentation.

Kaylen, M., D.L. Van Dyne, Y.S. Choi, and M. Blase. 2000. "Economic Feasibility of Producing Ethanol from Lignocellulosic Feedstocks." *Bioresource Technology* **72**:19-32.

Khanna, Madhu. 2008. "Cellulosic Biofuels: Are they Economically Viable and Environmentally Sustainable?" *Choices* **23(3)**:16-19.

Khanna, Madhu and Basanta Dhungana. November 2007. "Economics of Alternative Feedstocks." Chapter 8 of "Corn-based Ethanol in Illinois and the U.S.: A Report from the Department of Agricultural and Consumer Economics, University of Illinois." *Department* *of Agricultural and Consumer Economics, University of Illinois*. http://www.farmdoc.uiuc.edu/policy/research_reports/ethanol_report/index.html.

Khanna M, Dhungana B., Clifton-Brown J. June 2008 "Costs of Producing *Miscanthus* and Switchgrass for Bioenergy in Illinois." *Biomass and Bioenergy* **32:**482-493.

Kiniry, J., K. Cassida, M. Hussey, J. Muir, W. Ocumpaugh, J. Read, R. Reed, M. Sanderson, B. Venuto, and J. Williams. 2005. "Switchgrass Simulation by the ALMANAC model at Diverse Sites in the Southern US." *Biomass and Bioenergy* **29**:419-425.

Krissek, Greg. February 13, 2008. "Future Opportunities and Challenges for Ethanol Production and Technology." *ICM*. Presentation.

Kszos, L., S. McLaughlin, and M. Walsh. 2002. "Bioenergy From Switchgrass: Reducing Production Costs by Improving Yield and Optimizing Crop Management." Bioenergy 2002, Bioenergy for the Environment, Boise, ID, September 22-26, 2002.

Kumar, A. J. Cameron, and P. Flynn. 2003. "Biomass Power Cost and Optimum Plant Size in Western Canada." *Biomass and Bioenergy* **24**:445-464.

Kumar, A., J. Cameron, and P. Flynn. 2005. "Pipeline Transport and Simultaneous Saccharification of Corn Stover." *Bioresource Technology* **96:**819-829.

Kumar, A. and S. Sokhansanj. 2007. "Switchgrass (*Panicum vigratum,* L.) Delivery to a Biorefinery using Integrated Biomass Supply Analysis and Logistics (IBSAL) Model." Science Direct. *Bioresource Technology* **98**:1033-1044.

Lewandowski, I., J. Clifton-Brown, J. Scurlock, and W. Huisman. 2000. "*Miscanthus*: European Experience with a Novel Energy Crop." *Biomass and Bioenergy* **19**:209-227.

Lewandowski, I., J. Scurlock, E. Lindvall, and M. Christou. 2003. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe." *Biomass and Bioenergy* **25**:335-361

Mapemba, LD, FM Epplin, RL Huhnke, CM Taliaferro. 2008. "Herbaceous Plant Biomass Harvest and Delivery Cost with Harvest Segmented by Month and Number of Harvest Machines Endogenously Determined." *Biomass and Bioenergy*. doi:10.1016/j.biombioe.2008.02.003

Mapemba, L., F. Epplin, C. Taliaferro, and R. Huhnke. 2007. "Biorefinery Feedstock Production on Conservation Reserve Program Land." *Review of Agricultural Economics* **29**:227-246.

McAloon, A., Taylor, F., Yee, W., Ibsen, K. and R. Wooley. October 2000. "Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks." *U.S. Department of Agriculture and U.S. Department of Energy*. NREL/TP-580-28893.

McCarl, B., D. Adams, R. Alig, and J. Chmelik. 2000. Competitiveness of Biomass-fueled Electrical Power Plants. *Annals of Operations Research* **94**:37-55.

McLaughlin, S. B., D. G. de la Torre Ugarte, C. T. Garten, Jr., L. R. Lynd, M. A. Sanderson, V. R. Tolbert, and D. D. Wolf. 2002. High-value renewable energy from prairie grasses. *Environ. Sci. Technol* **36**:2122-2129.

McLaughlin, S. B. and L. A. Kszos. 2005. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. *Biomass and Bioenergy* **28**:515-535.

Muir, J., M. Sanderson, W. Ocumpaugh, R. Jones, and R. Reed. 2001. "Biomass Production of 'Alamo' Switchgrass in Response to Nitrogen, Phosphorus, and Row Spacing. *Agronomy Journal* **93**:896-901.

National Agricultural Statistics Service (NASSa), Agricultural Statistics Board, U.S. Department of Agriculture. July 2007. "Agricultural Prices 2006 Summary." http://usda.mannlib.cornell.edu/usda/current/AgriPricSu/AgriPricSu-07-20-2007_revision.pdf.

National Agricultural Statistics Service (NASSb), Agricultural Statistics Board, U.S. Department of Agriculture. December 2007. "Agricultural Prices December 2007." http://usda.mannlib.cornell.edu/usda/nass/AgriPric//2000s/2007/AgriPric-12-28-2007.pdf.

Nelson, R., J. Ascough, and M. Langemeier. 2006. "Environmental and Economic Analysis of Switchgrass Production for Water Quality Improvement in Northeast Kansas." *Journal of Environmental Management* **79**:336-347.

Ocumpaugh, W., M. Hussey, J. Read, J. Muir, F. Hons, G. Evers, K. Cassida, B. Venuto, J. Grichar, and C. Tischler. 2003. "Evaluation of Switchgrass Cultivars and Cultural Methods for Biomass Production in the South Central U.S." Report for U.S. Department of Energy, Office of Biomass. ORNL/SUB-03-19SXY091C/01.

Parrish, D., D. Wolf, J. Fike, and W. Daniels. 2003. "Switchgrass as a Biofuels Crop for the Upper Southeast: Variety Trials and Cultural Improvements." Report for U.S. Department of Energy, Office of Biomass. ORNL/SUB-03-19XSY163/01.

Perlack, Bob. November 19, 2007. "Overview of Plant Feedstock Production for Biofuels: Current Technologies, Challenges, and Potential Improvement." *Oak Ridge National Laboratory*. Presentation.

Perlack, R. and A. Turhollow. 2002. "Assessment of Options for the Collection, Handling, and Transport of Corn Stover." *Oak Ridge National Laboratory*. ORNL/TM-2002/44.

Perlack, R. and A. Turhollow. 2003. "Feedstock Cost Analysis of Corn Stover Residues for Further Processing." *Energy* **28**:1395-1403.

Perrin, R., K. Vogel, M. Schmer, and R. Mitchell. 2008. "Farm-Scale Production Cost of Switchgrass for Biomass." *BioEnergy Research* **1:** 91-97.

Petrolia, DR. July 2008. "The Economics of Harvesting and Transporting Corn Stover to Fuel Ethanol: A Case Study for Minnesota." *Biomass and Bioenergy* **32(7):**603-612.

Popp, M. and R. Hogan, Jr. 2007. "Assessment of Two Alternative Switchgrass Harvest and Transport Methods." Farm Foundation Conference Paper. St. Louis, Missouri, April 12-13.

Prewitt, R. M. Montross, S. Shearer, T. Stombaugh, S. Higgins, S. McNeill, and S. Sokhansanj. 2007. "Corn Stover Availability and Collection Efficiency Using Typical Hay Equipment." *Transactions of the ASABE* **50:**705-711.

Quick, G. February 2003. "Single-Pass Corn and Stover Harvesters: Development and Performance." Proceedings of the International Conference on Crop Harvesting and Processing February 2003. ASAE Publication Number 701P1103e.

Renewable Fuels Association (RFA). Industry Statistics: Historic U.S. Fuel Ethanol Production and Ethanol Industry Overview. Retrieved January 26, 2010. http://www.ethanolrfa.org/industry/statistics/#A

Reynolds, J., C. Walker, and M. Kirchner. 2000. "Nitrogen Removal in Switchgrass Biomass Under Two Harvest Systems." *Biomass and Bioenergy* **19**: 281-286.

Sanderson, M. 2008. "Upland Switchgrass Yield, Nutritive Value, and Carbon Changes under Grazing and Clipping." *Agronomy Journal* **100**(3): 510-516.

Schechinger, T. and J. Hettenhaus. April 2004. "Corn Stover Harvesting: Grower, Custom Operator, and Processor Issues and Answers." Oak Ridge National Laboratory. ORNL/SUB-04-4500008274-01.

Schmer, M., K. Vogel, R. Mitchell, L. Moser, K. Eskridge, and R. Perrin. 2006. "Establishment Stand Thresholds for Switchgrass Grown as a Bioenergy Crop." *Crop Science* **46**:157-161.

Searcy, E., P. Flynn, E. Ghafoori, and A. Kumar. 2007. "The Relative Cost of Biomass Energy Transport." *Applied Biochemistry and Biotechnology* **136-140**:639-652.

Shinners, K., G. Boettcher, R. Muck, P. Wimer, and M. Caser. July 2006. "Drying, Harvesting and Storage Characteristics of Perennial Grasses as Biomass Feedstocks." 2006 ASABE Annual International Meeting. Paper Number: 061012.

Smeets, E., I. Lewandowski, and A. Faaij. 2009. "The Economical and Environmental Performance of Miscanthus and Switchgrass Production and Supply Chains in a European Setting." *Renewable and Sustainable Energy Reviews* **13**:1230-1245.

Sokhansanj, Shahab and Anthony Turhollow. September 2002. "Baseline Cost for Corn Stover Collection." *Applied Engineering in Agriculture* **18(5)**:525-530.

Stampfl, P., J. Clifton-Brown, and M. Jones. 2007. "European-wide GIS-based Modeling System for Quantifying the Feedstock from *Miscanthus* and the Potential Contribution to Renewable Energy Targets." *Global Change Biology* **13**:2283-2295.

Summit Ridge Investments, LLC. October 2007. "Eastern Harwood Forest Region Woody Biomass Energy Opportunity."

Suzuki, Yoshinori (Principle Investigator). February 2006. "Estimating the Cost of Transporting Corn Stalks in the Midwest." Iowa State University College of Business: Business and Partnership Development.

Taheripour, F. and W. Tyner. 2008. "Ethanol Policy Analysis – What Have We Learned So Far?" *Choices* **23(3)**:6-11.

Taliaferro, C. 2002. "Breeding and Selection of New Switchgrass Varieties for Increased Biomass Production." Report for U.S. Department of Energy, Office of Biomass. ORNL/SUB-02-19XSY162C/01.

Thomason, W., W. Raun, G. Johnson, C. Taliaferro, K. Freeman, K. Wynn., and R. Mullen. 2005. "Switchgrass Response to Harvest Frequency and Time and Rate of Applied Nitrogen." *Journal of Plant Nutrition* **27**:1199-1226.

Tiffany, D., B. Jordan, E. Dietrich, and B. Vargo-Daggett. June 2006. "Energy and Chemicals form Native Grasses: Production, Transportation and Processing Technologies Considered in the Northern Great Plains." Department of Applied Economics. College of Food, Agricultural and Natural Resource Sciences, University of Minnesota. Staff Paper P06-11.

Tokgoz, S., A. Elobeid, J. Fabiosa, D. Hayes, B. Babcock, T. Yu, F. Dong, C. Hart, and J. Beghin. May 2007. "Emerging Biofuels: Outlook of Effects on U.S. Grain, Oilseed, and Livestock Markets." CARD. Staff Report 07-SR 101.

United States Congress. Food, Conservation, and Energy Act of 2008.

United States Department of Agriculture and Department of Energy. "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply." April 2005. ORNL/TM-2005/66.

United States Department of Agriculture, Forest Services. April 2003. "A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States." http://www.fs.fed.us/research/pdf/Western_final.pdf

United States Department of Agriculture, Forest Services. March 2005. "A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States." http://www.fs.fed.us/rm/pubs/rmrs_gtr149.pdf

Vargas, L., M. Andersen, C. Jensen, and U. Jorgensen. 2002. "Estimation of Leaf Area Index, Light Interception and Biomass Accumulation of *Miscanthus Sinensis* 'Goliath' from Radiation Measurements." *Biomass and Bioenergy* **22**:1-14.

Vadas, P., K. Barneet, and D. Undersander. March 2008. "Economics of Ethanol Prodcution from Alfalfa, Corn and Switchgrass in the Upper Midwest, USA." *BioEnergy Research* **1**:44-55.

Vogel, K., J. Brejda, D. Walters, and D. Buxton. 2002. "Switchgrass Biomass Production in the Midwest USA: Harvest and Nitrogen Management." *Agronomy Journal* **94**:413-420.

Walsh, Marie. "Switchgrass." SunGrant BioWeb. Retrieved February 5, 2008. Last update: May 8, 2008. http://bioweb.sungrant.org/Technical/Biomass+Resources/Agricultural+Resources/New+Crops/Herbaceous+Crops/Switchgrass/Default.htm

The White House. (2007, January 23). *President Bush Delivers State of the Union Address.* January 23, 2007. Retrieved March 22, 2007. http://www.whitehouse.gov/news/releases/2007/01/20070123-2.html.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. Jan/Feb 2004. "Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review." *Agronomy Journal* **96**:1-17.

Wright, M. and R. Brown. 2007. "Comparative Economics of Biorefineries Based on the Biochemical and Thermochemical Platforms." *Biofuels Bioproducts & Biorefining* **1**:49-56.

Appendix 1: Summary of Research Estimates and Sources

Appendix Table 1-1: Cellulosic Ethanol Production Research Estimates

Type of Cost	Assumption	Value cited	Value in 2007	Reference
Oil Price		$60/barrel		Elobeid et al. (2006)
EV		0.667		Elobeid et al. (2006)
		0.667		Tokgoz et al. (2007)
Tax credit	Cellulosic	$1.01/gallon		FCEA, 2008
By-Product credit	Cellulosic	2.28 kWh/gal	$0.14-0.21/gal[63]	Aden et al. (2002)
		$0.11/gal	$0.16/gal	Khanna and Dhungana (2007)
		$0.12/gallon[64]		Khanna (2008)
Investment Cost	69.3 MMGY	$197.4 million	$0.85/gal[65]	Aden et al. (2002)
	50 MMGY	$294 million		Wright and Brown (2007)
	100 MMGY	$400 million		Taheripour and Tyner (2008)
	Stover (69.6 MMGY)	$202.2 million ($0.46/gal)	$0.50[66]	Huang et al. (2009)
	SG(64 MMGY)	$212.1 million ($0.53/gal)	$0.58	
	Hybrid Poplar (68 MMGY)	$203.3 million ($0.50/gal)	$0.545	
	Aspen Wood (86 MMGY)	$187 million ($0.34/gal)	$0.37	
Partial Variable Cost		$0.11/gallon		Aden et al. (2002)
Other Costs		$0.11/gallon		Aden et al. (2002)
Enzyme Cost		$0.07-0.20/gallon ($0.10 mean)		Aden et al. (2002)
		$0.14-0.18/gallon		Bothast (2005)
		$0.18/gallon		Jha et al. (Prst)
		$0.40-$1.00/gallon		Industry Source
		$0.10-0.25/gallon		Tiffany et al. (2006)
Operating Costs	Stover	$1.42/gallon[67]	$1.58/gal	Huang et al. (2009)
	SG (crop)	$1.73/gallon	$1.92/gal	
	SG (grass)	$1.86/gallon	$2.06/gal	
	Hybrid Poplar	$1.83/gallon	$2.03/gal	
	Aspen Wood	$1.56/gallon	$1.73/gal	
Ethanol Yield		87.9		Aden et al. (2002)
		79.2		Khanna and Dhungana

[63] Updated using EIA (2008).
[64] Not updated since author did not provide year of estimate.
[65] Updated value of Aden et al.'s per gallon cost.
[66] Huang et al.'s (2009) investment cost estimates were amortized over 10 years at 10 percent and updated using USDA NASS Building Materials Prices from 1999-2007 (NASS, 2007a,b).
[67] Operating Costs were updated using USDA NASS Machinery Prices from 1999-2007 (NASS, 2007a,b).

			(2007)
		72	McAloon et al. (2000)
		70	Tokgoz et al. (2007)
		70	Petrolia (2008)
		96	Comis (2006)
		60-140	Krissek (2008)
		60-140	Crooks (2006)
		80	Perlack and Turhollow (2002)
		87.3	Khanna (2008)
		80-90	BRDI (2008)
		89.5 (Woody)	BRDI (2008)
		80-120	Atchison and Hettenhaus (2003)
		67.8-89.7	Tiffany et al. (2006)
	Stover	89.8	Huang et al. (2009)
	Switchgrass	82.7	
	Hybrid Poplar	88.2	
	Aspen Wood	111.4	
Online Days		350	Aden et al. (2002)
		350	Huang et al. (2009)

Appendix Table 1-2: Nutrient and Replacement[68]

Feedstock	Type of Cost	Cost per ton (cited)	Cost per ton (2007$)	Reference
Corn Stover		$7	$14.40	Aden et al. (2002)
Corn Stover		$6.40-12.20[69]		Atchison and Hettenhaus (2003)
Corn Stover		$15.64	$15.64	Brechbill and Tyner (2008a)
Corn Stover		$10.20	$14.10	Hoskinson et al. (2007)
Corn Stover		$7.26 ($8/Mg)	$10	Huang et al. (2009)
Corn Stover	Whole plant harvest	$9.70	$13.30	Karlen and Birrell (Prst)
Corn Stover	Harvest cob & top 50%	$9.50	$13.10	Karlen and Birrell (Prst)
Corn Stover	Bottom 50% harvest	$10.10	$13.90	Karlen and Birrell (Prst)
Corn Stover		$4.60	$8.40	Khanna and Dhungana (2007)
Corn Stover		$10	$21	Perlack and Turhollow (2003)
Corn Stover		$4.20	$4.20	Petrolia (2008)
Switchgrass		$10.80	$19.77	Khanna et al. (2008)
Switchgrass		$6.70	$12.10	Perrin et al. (2008)
Miscanthus		$2.50	$4.60	Khanna et al. (2008)

[68] Nutrient and Replacement costs were updated using USDA NASS Agricultural Fertilizer Prices from 1999-2007 (NASS, 2007a,b).
[69] Price not updated

Appendix Table 1-3: Harvest and Maintenance[70]				
Feedstock	**Type of Cost**	**Cost per ton (cited)**	**Cost per ton (2007$)**	**Reference**
Corn Stover	Baling and staging	$26	$47	Aden et al. (2002)
Corn Stover	Custom Harvest			Brechbill and Tyner (2008a)
	Bale	$7.47	$7.47	
	Rake and Bale	$8.84	$8.84	
	Shred, Rake, and Bale	$10.70	$10.70	
Corn Stover or Switchgrass	Move to fieldside	$2	$2	Brechbill and Tyner (2008a)
Corn Stover	Harvest	$14	$14	Edwards (2007)
Corn Stover	Baling, stacking and grinding	$26	$45	Hess et al. (2007)
Corn Stover	Combine, Shred, Bale and Stack	$19.16	$24.33	Haung et al. (2009)
Corn Stover	Harvest	$35.41-36.58	$35.41-36.58	Khanna (2008)
Corn Stover	Collection	$31-36	$66-77	McAloon et al. (2000)
Corn Stover	Collection	$35-46	$64-84	McAloon et al. (2000)
Corn Stover	Collection	$17.70	$17.70	Perlack (2007) Presentation
Corn Stover	Up to Storage	$20-21	$36-39	Sokhansanj and Turhollow (2002)
Corn Stover		$28	$36	Suzuki (2006)
Switchgrass	Custom Harvest			Brechbill and Tyner (2008a)
	Bale	$2.01	$2.01	
	Rake and Bale	$3.09	$3.09	
	Shred, Rake and Bale	$4.79	$4.79	
Switchgrass	Harvest	$32	$32	Duffy (2007)
Switchgrass	Harvest (square bales)	$21.86	$27.80	Huang et al. (2009)
Switchgrass	Harvest	$27.80-34.72	$27.80-34.72	Khanna (2008)
Switchgrass	Harvest, maintenance and establishment	$123.50/acre	$210/acre	Khanna and Dhungana (2007)
Switchgrass	Harvest	$35	$58	Khanna et al. (2008)
Switchgrass	Collection	$12-22	$16-28	Kumar and Sokhansanj (2007)
Switchgrass	Harvest	$15	$26	Perrin et al. (2008)
Prairie grasses (includes SG)	Harvest	$17		Tiffany et al. (2006)
Miscanthus	Harvest	$18.72-32.65	$18.72-32.65	Khanna (2008)
Miscanthus	Harvest, maintenance, and establishment	$301/acre	$512/acre	Khanna and Dhungana (2007)
Miscanthus	Harvest	$33	$54	Khanna et al. (2008)

[70] Harvest and maintenance costs were updated using USDA NASS Agricultural fuel, machinery and labor prices from 1999-2007 (NASS, 2007a,b).

Non-specific		$10-30	$15-45	Mapemba et al. (2007)
Non-specific		$23	$38	Mapemba et al. (2008)
Hybrid Poplar and Aspen Wood	Logging Cost			Huang et al. (2009)
	Range	$14-28	$17.80-34.60	
	Assumed	$14.50	$18.40	
	Chipping Cost			
	Range	$12-27	$15.20-34.30	
	Assumed (Minnesota)	$12.70	$16.10	
Aspen Wood	Stumpage	$51.90	$66	Huang et al. (2009)
Woody Biomass	Cut and extract to roadside	$35-87[71]		USDA FS (2003, 2005)
Woody Biomass	Roadside	$40-46	$40-46	BRDI (2008)
Woody Biomass	Stumpage	$4	$4	BRDI (2008)
Short-run Woody	Harvest/Collection	$17-29/acre	$17-29/acre	BRDI (2008)

Appendix Table 1-4: Transportation Cost[72]

Feedstock	Type of Cost	Cost cited	Cost (2007$)	Reference
Corn Stover	Per ton	$13	$31	Aden et al. (2002)
Corn Stover	10 miles	$3.40	$3.40[73]	Atchison and Hettenhaus (2003)
	15 miles	$5.10	$5.10	
	30 miles	$10.20	$10.20	
	40 miles	$13.50	$13.50	
	50 miles	$17	$17	
Corn Stover	Own equipment	(per ton)		Brechbill and Tyner (2008a)
	10 miles	$3.31-6.18	$3.31-6.18[74]	
	20 miles	$4.65-7.52	$4.65-7.52	
	30 miles	$5.99-8.86	$5.99-8.86	
	40 miles	$7.33-7.71	$7.33-7.71	
	50 miles	$8.67-9.05	$8.67-9.05	
Corn Stover or Switchgrass	Custom per ton			Brechbill and Tyner (2008a)
	10 miles	$3.92	$3.92[75]	
	20 miles	$6.69	$6.69	
	30 miles	$9.46	$9.46	
	40 miles	$12.23	$12.23	
	50 miles	$15	$15	
Corn Stover	Per ton	$8.85	$12.50	English et al. (2006)
Corn Stover	Per ton	$10.25	$27	Hess et al. (2007)
Corn Stover	Per ton	$10.80	$10.80	Perlack (2007) Presentation
Corn Stover	Per ton	$4.20-10.50	$11-$27.70	Perlack and Turhollow (2002)
Corn Stover	Per ton	$10.90	$13.80	Vadas et al. (2008)

[71] Price not updated
[72] Transportation costs were updated using USDA NASS Agricultural fuel prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[73] Prices not updated
[74] Authors used 2006 wages and March 2008 fuel costs
[75] Prices not updated

Corn Stover or Switchgrass	Custom loading	$1.15	$1.15	Brechbill and Tyner (2008a)
	Custom DVC	$0.28	$0.28	
	Owned DVC	$0.12	$0.12	
Corn Stover or Switchgrass	Average DVC	$0.20	$0.20	Brechbill and Tyner (2008a, 2008b)
Corn Stover	DFC	$6.90	$9.71	Huang et al. (2009)
	DVC	$0.16	$0.23	
Corn Stover	DVC[76]	$0.15	$0.35	Kaylen et al. (2000)
Corn Stover	Max DVC for positive NPV	$0.28	$0.66	Kaylen et al. (2000)
Corn Stover	DVC	$0.16	$0.38	Kumar et al. (2003)
	DFC	$3.60	$8.60	
Corn Stover	DVC	$0.08-0.29	$0.17-0.63	Kumar et al. (2005)
	DFC[77]	$4.50	$9.80	
	DFC range	$0-6	$0-13.3	
Corn Stover	DVC			Petrolia (2008)
	0-25 miles	$0.13-0.23	$0.13-0.23	
	25-100 miles	$0.10-0.19	$0.10-0.19	
	> 100 miles	$0.09-0.16	$0.09-0.16	
	DFC square bales	$1.70	$1.70	
	DFC round bales	$3.10	$3.10	
Corn Stover	DVC	$0.18	$0.32	Searcy et al. (2007)
	DFC	$4.00	$7.30	
Switchgrass	Own equipment	(per ton)		Brechbill and Tyner (2008a)
	10 miles	$3.13-3.93	$3.13-3.93[78]	
	20 miles	$4.47-5.27	$4.47-5.27	
	30 miles	$5.81-6.61	$5.81-6.61	
	40 miles	$7.15-7.95	$7.15-7.95	
	50 miles	$8.49-9.29	$8.49-9.29	
Switchgrass	Per ton	$14.75	$14.75	Duffy (2007)
Switchgrass or *Miscanthus*	Per ton (50 miles)	$7.90	$17.10	Khanna et al. (2008)
Switchgrass	Per ton	$19.20-23	$27-32.40	Kumar and Sokhansanj (2007)
Switchgrass	Per ton	$13	$28	Perrin et al. (2008)
Switchgrass	Per ton	$10.90	$13.80	Vadas et al. (2008)
Switchgrass	DFC	$3.39	$4.78	Huang et al. (2009)
	DVC	$0.16	$0.23	
Native Prairie [includes SG]	Per ton	$4[79]		Tiffany et al. (2006)
Non-specific	Per ton	$7.40-19.30	$13.7-35.60	Mapemba et al. (2007)
Non-specific	Per ton	$14.50	$31.50	Mapemba et al. (2008)
Hybrid Poplar	DFC	$4.13	$5.80	Huang et al. (2009)

[76] DVC is distance variable cost in per ton per mile
[77] DFC is distance fixed cost per ton
[78] Authors used 2006 wages and March 2008 fuel costs
[79] Price not updated

and Aspen Wood				
	DVC	$0.16	$0.23	
Woody Biomass	Per ton		$11-22	Summit Ridge Investments (2007)
Woody Biomass	DVC (range)	$0.20-0.60	$0.20-0.60[80]	USDA FS (2003, 2005)
	DVC (used)	$0.35	$0.35	

Appendix Table 1-5: Distance

Distance	Type	Reference
10-50	One-way	Atchison and Hettenhaus (2003)
75	One-way max	BRDI (2008)
5-50	One-way	Brechbill and Tyner (2008a, 2008b)
50	One-way max	English et al. (2006)
50	Round-trip	Khanna et al. (2008)
46-134	Round-trip	Mapemba et al. (2007)
22-61	One-way	Perlack and Turhollow (2002)
22-62	One-way	Perlack and Turhollow (2003)
50	One-way max	Taheripour and Tyner (2008)
50	One-way	Tiffany et al. (2006)
50	One-way	Vadas et al. (2008)
100	One-way (Woody)	USDA FS (2003,2005)

Appendix Table 1-6: Storage[81]

Feedstock	Type of Cost	Cost per ton (cited)	Cost per ton (2007$)	Reference
Corn Stover		$4.44	$5.64	Hess et al. (2007)
Corn Stover		$4.39-21.95	$4.39-21.95	Khanna (2008)
Corn Stover	Round bales	$6.82	$6.82	Petrolia (2008)
	Square bales	$12.93	$12.93	
Corn Stover or Switchgrass	Square bales	$7.25	$7.90	Huang et al. (2009)
Switchgrass		$16.67	$16.67	Duffy (2007)
Switchgrass		$4.43-21.68	$4.43-21.68	Khanna (2008)
Switchgrass		$4.14	$5.18	Khanna et al. (2008)
Miscanthus		$4.64-23.45	$4.64-23.45	Khanna (2008)
Miscanthus		$4.40	$5.50	Khanna et al. (2008)
Non-specific		$2	$2.18	Mapemba et al. (2008)
Hybrid Poplar or Aspen Wood	Chips	$0[82]	$0	Huang et al. (2009)

Appendix Table 1-7: Establishment and Seeding[83]

[80] Price not updated
[81] Storage costs were updated using USDA NASS Agricultural building material prices from 1999-2007 [NASSa, 2007; NASSb, 2007].
[82] Assume wood is kept on stump until needed.

Feedstock	Type of Cost	Land rent included	Cost per acre (cited)	Cost per acre (2007$)	Reference
Switchgrass		Yes	$200	$200	Duffy (2007)
Switchgrass	Grassland	No	$134	$180	Huang et al. (2009)
	Cropland (includes fertilizer)		$161	$216	
Switchgrass	PV per ton	No	$7.21/ton	$12.60/ton	Khanna et al. (2008)
	10 year PV per acre		$142.30	$249	
	Amortized				
	4% over 10 years		$17.30	$30.25	
	8% over 10 years		$20.70	$36.25	
Switchgrass		No	$25.76	$46	Perrin et al. (2008)
		Yes	$85.46	$153	
Switchgrass		Yes	$72.50-110	$88.50-134	Vadas et al. (2008)
Miscanthus	PV per ton	No	$2.29/ton	$4/ton	Khanna et al. (2008)
	20 year PV per acre		$261	$457	
	Amortized				
	4% over 20 years		$19	$33.20	
	8% over 20 years		$26.20	$45.87	
Miscanthus	Total Cost	No	$1206-2413		Lewandowski et al. (2003)
	Amortized				
	4% over 20 years		$88-175	$176-350	
	8% over 20 years		$121-242	$242-484	
Hybrid Poplar	Includes nutrient cost (cropland)	No	$35	$47	Huang et al. (2009)

Appendix Table 1-8: Opportunity Cost[84]

Feedstock	Type of Cost	Cost per acre (cited)	Cost per acre (2007$)	Reference
Corn Stover	Feed value	$59.50/ton	$59.50/ton	Edwards (2007)
	2.4 tons/acre	$142.80	$142.80	
Corn Stover	Lost profits	$22-58	$22-58	Khanna and Dhungana (2007)
Switchgrass	Cash Rents	$70/acre ($14/ton)	$70/acre ($14/ton)	Brechbill and Tyner (2008a)
Switchgrass	Lost profits	$78-231	$78-231	Khanna and Dhungana (2007)
Switchgrass or *Miscanthus*	Lost profits	$78	$76	Khanna et al. (2008)
Miscanthus	Lost profits	$78-231	$78-231	Khanna and Dhungana (2007)
Non-specific		$78	$76	Khanna et al. (2008)

[83] Establishment and Seeding costs were updated using USDA NASS Agricultural fuel and seed prices from 1999-2007 [NASSa, 2007; NASSb, 2007].

[84] Opportunity costs were updated using USDA NASS Agricultural land rent prices from 1999-2007 [NASSa, 2007; NASSb, 2007].

Non-specific	Lost CRP payments if harvest every year	$35	$36	Mapemba et al. (2008)
Non-specific	Lost CRP if harvest once every 3 years	$10.10	$10.40	Mapemba et al. (2008)
Non-specific	Non-CRP land crops	$10/ton	$10.30/ton	Mapemba et al. (2008)
Woody Biomass	Alternative use	$0-25	$0-25	Summit Ridge Investments (2007)
Woody Biomass	Chip value	$30/ton	$30/ton[85]	USDA FS (2003, 2005)

Appendix Table 1-9: Corn Stover Yield

Reference	Location	Assumptions	Estimated Yield (tons acre^{-1})
Atchison and Hettenhaus (2003)	Not specific		2-3.8
Atchison and Hettenhaus (2003)	Not specific	130 bu/acre yield	0-2.6
		170 bu/acre yield	0-3.6
		200 bu/acre yield	0-4.3
BRDI (2008)	Not specific		3
Brechbill and Tyner (2008a)	Indiana	Bale	1.62
		Rake and Bale	2.23
		Shred, Rake and Bale	2.98
Duffy and Nanhou (2001)	Iowa	Four scenarios	1.5, 3, 4, and 6
Edwards (2007)	Iowa		2.4
Haung et al. (2009)	Minnesota	Produced	2.54
Khanna (2008)	Illinois	Produced	2.4-4
		Delivered	1.8-1.9
Khanna and Dhungana (2007)	Illinois	Soil tolerance	2.02
Lang (2002)	Not specific	Total produced	
		125 bu/acre	3.5
		140 bu/acre	3.92
		> 140 bu/acre	4
Perlack and Turhollow (2002)	Not specific		1.1
Prewitt et al. (2007)	Kentucky	Collected	0.8-2.2
Quick (2003)	Iowa	Total produced	4.2
		Removable	2.94
Sokhansanj and Turhollow (2002)	Midwest	Produced	3.6
		Delivered	1.5
Schechinger and Hettenhaus (2004)	Iowa and Wisconsin	Collected (trial)	1.25-1.5
Vadas et al. (2008)	Wisconsin	2000-2005 mean	2.31-3

Appendix Table 1-10: Switchgrass Yield

Reference	Location (Region)	Assumptions	Estimated Yield

[85] Price not updated since no year was provided for initial estimate

			(tons acre^{-1})
Berdahl et al. (2005)	N. Dakota	Field trials	
		Mean	1.12-4.1
		Strains:	
		Dacotah	1.11-4.22
		ND3743	0.91-3.92
		Summer	1.18-4.38
		Sunburst	1.43-5.57
		Trailblazer	1.15-4.88
		Shawnee	1.06-4.5
		OK NU-2	0.89-4.18
		Cave-in-Rock	0.97-4.27
Bouton et al. (2002)	Alabama	Kanlow (average)	5.9
		Alamo (average)	6.0
Brechbill and Tyner (2008a)	Indiana		5
BRDI (2008)	Not Specific		4.2-10.3
Cassida et al. (2005)	Texas	Alamo (3-4 years)	4.9-8.8
		Caddo (3-4 years)	2.2-2.7
	Louisiana	Alamo (3 years)	4.8
		Caddo (3 years)	0.5
	Arkansas	Alamo (3 years)	7.5
		Caddo (3 years)	3.3
Comis (2006)	Southeast		7-16
	Western Corn Belt		5-6
	North Dakota		1-4
Duffy (2007)	Iowa		4
Fike et al. (2006a)	SE	Plot trials	6.33
			4.64-8.5
Fike et al. (2006b)	Southeast	CIR (1 cut)	3.9-7.3
		Shelter (1 cut)	3.7-6.8
		Alamo (1 cut)	4.8-9.8
		Kanlow (1 cut)	5.4-9.5
		CIR (2 cut)	5.8-9.5
		Shelter (2 cut)	4.9-9.1
		Alamo (2 cut)	6-10
		Kanlow (2 cut)	6-9.5
Gibson and Barnhart (2007)	Iowa		1-4
			2-6.4
Heaton et al. (2004a)		Peer-reviewed articles	4.46
Huang et al. (2009)	Minnesota	Cropland and grassland	4.9
Khanna (2008)	Illinois	Delivered	2.3-2.5
Khanna and Dhungana (2007)	Iowa and Illinois	Field Trials	2.58
Khanna et al. (2008)	Illinois		3.8
		10 year PV	19.74
Kiniry et al. (2005)	Louisiana	3 years of data (avg)	5.5
	Arkansas		7.7
	Texas		8.3-10
	Texas	7 years of data (avg)	6.6
Kszos et al. (2002)		Assumptions	

		Lake States	4.8
		Corn Belt	5.98
		Southeast	5.49
		Appalachian	5.84
		North Plains	3.47
		South Plains	4.3
		North East	4.87
Lewandowski et al. (2003)	Southern and Mid-Atlantic	Research block	
		Average	7.14
		Best	9.8
Lewandowski et al. (2003)	Texas, Upper South	Alamo (1 cut)	5.4-5.9
	Alabama	Alamo (1 cut)	11.6
	Alabama	Alamo (2 cut)	15.4
	Texas, Upper South	Kanlow (1 cut)	4.5-5.5
	Alabama	Kanlow (1 cut)	8.3
	Alabama	Kanlow (2 cut)	10.3
	Britain	Kanlow (3-4 years)	5
	Texas, Upper South	Cave-in-Rock (1 cut)	2.4-4.2
	Alabama	Cave-in-Rock (1 cut)	4.2
	Alabama	Cave-in-Rock (2 cut)	4.6
	Britain	Cave-in Rock (3-6 years)	4.7
McLaughlin et al. (2002)		US average	4.2
McLaughlin and Kszos (2005)		Farm trials (avg)	
	VA, TN, WV, KY, NC	Alamo (1 cut)	6.2
	TX, AR, LA	Alamo (1 cut)	6-8.5
	Iowa	Alamo (1 cut)	5.4
	AL, GA	Alamo (1 cut)	5.8-7.2
	VA, TN, VW, KY, NC	Alamo (2 cut)	7
	Alabama	Alamo (2 cut)	7.2-10.3
	VA, TN, WV, KY, NC	Kanlow (1 cut)	6.2
	Iowa	Kanlow (1 cut)	5.8
	AL, GA	Kanlow (1 cut)	5.2-7
	Nebraska	Kanlow (1 cut)	9.2
	Alabama	Kanlow (2 cut)	6.9-8.1
	Nebraska	Cave-in-rock (1 cut)	7.3
	Kansas	Rockwell (1 cut)	4.2
	Kansas	Shelter (1 cut)	4.2
	North Dakota	Sunburst (1 cut)	4.9
	North Dakota	Trailblazer (1 cut)	4.4
		Best	
	VA, TN, WV, KY, NC	Alamo (1 cut)	12.2
	TX, AR, LA	Alamo (1 cut)	11
	Iowa	Alamo (1 cut)	7.8
	Alabama	Alamo (1 cut)	15.4
	VA, TN, VW, KY, NC	Alamo (2 cut)	11.3
	Alabama	Alamo (2 cut)	15.4

	VA, TN, WV, KY, NC	Kanlow (1 cut)	10.4
	AL, GA	Kanlow (1 cut)	11
	North Dakota	Sunburst (1 cut)	6.2
	North Dakota	Trailblazer	5.4
Muir et al. (2001)	Texas	Max (Alamo)	10
		Average (2 sites)	4.8-6.5
Nelson et al. (2006)	Kansas	Predicted yields	
		0-200 lbs/acre N	2.5-5.9
		100 lbs/acre N	4.6
Ocumpaugh et al. (2003)	Texas	Alamo (1 cut)	1.2-9
		Alamo (2 cut)	1.3-8.6
Parrish et al. (2003)		Upland (1 cut)	4.8-5.3
		Upland (2 cut)	6.5-6.7
		Lowland (1 cut)	6.6-7
		Lowland (2 cut)	6.8-7.3
Perrin et al. (2008)	S. Dakota, Nebraska	Farm-scale	
		5 year average	2.23
		5 year range	1.7-2.7
		10 year average	3.12
		10 year range	2.6-3.5
Popp and Hogan (2007)	Arkansas	First year	0
		Second year	3
		Third+ year	5
Reynolds et al. (2000)	Tennessee	One-cut range	5-9
		Two-cut range	6.8-10.3
		Cave-in-rock (2 cut)	8.7
		Alamo (2 cut)	8.9
		Kanlow (2 cut)	8.2
		Shelter (2 cut)	8.1
Sanderson (2008)	Pennsylvania	Mean (2 cut)	2.7
		Cave-in-rock	2.8
		Shawnee	2.7
		Trailblazer	2.6
		Mean (3 cut)	3.2
		Cave-in-rock	3.2
		Shawnee	3.2
		Trailblazer	3.2
Schmer et al. (2006)	Northern Great Plains	Field Trials	
		Mean	0.5-3.2
		Range	0-6.4
Shinners et al. (2006)	US	Previous	3.6-8.9
	Northern	Plot trials	2.3-4
Taliaferro (2002)	Kansas	Alamo	1.6
	Arkansas	Alamo	2.8
	Virginia	Alamo	2.8
	Oklahoma	Alamo	2..8
	Kansas	Kanlow	1.4
	Arkansas	Kanlow	2.9
	Virginia	Kanlow	2.5

	Oklahoma	Kanlow	2.8
Tiffany et al. (2006)	Northern Plains		4
Thomason et al. (2005)	Oklahoma	One cut	5.8
		Two Cut	5.6
		Three Cut	7.3
		Max Yield (2 harvest)	16.4
Vadas et al. (2008)	Upper Midwest	Nitrogen level	4-5.8
Vogel et al. (2002)	Iowa	Plot trials	5.2-5.6
	Nebraska		4.7-5
Walsh (2008)	VA, WV, TN, KY, NC, GA, AL, TX, AR, LA, ND, SD, IA (18 sites)	Alamo	5.35-6.9
	Same 18 sites	Kanlow	5.2-6.9
	Alabama	Max one year	15.4

Appendix Table 1-11: *Miscanthus* Yield

Reference	Location (Region)	Assumptions	Estimated Yield (tons $acre^{-1}$)
Christian et al. (2008)	EU	Field experiment	
		14 years	5.71
		3 years	3.43-11.73
Clifton-Brown and Lewandowski (2002)	Germany	First year average	0.85
		First year max	1.34
		Second year average	2.8
		Second year max	4.3
		Third year average	7.3
		Third year max	11.4
Clifton-Brown et al. (2001)	EU	First year average	0.85
		First year max	2.6
		First year min	0.16
		Second year average	3.8
		Second year max	12
		Third year max	18.2
Clifton-Brown et al. (2004)	EU	Peak	7.5-17.2
		Delayed	4.3-11.6
Heaton et al. (2004a)		Peer-reviewed articles	9.8
Heaton et al. (2004b)	US	Projection (mean)	13.36
		Range	10.93-17.81
Kahle et al. (2001)	Germany	Above ground	6.6-14.9
		Mean harvested	5.2
Khanna (2008)	Illinois	Potential	12-18
		Delivered	8.1-8.5
Khanna and Dhungana (2007)	Illinois	Simulated	8.9
Khanna et al. (2008)	Illinois	Average	14.5
		Range	12-17
		20 year PV	114.58

Lewandowski et al. (2000)	EU		4.5-17.8
Lewandowski et al. (2003)	EU		1.8-19.6
Smeets et al. (2009)	EU	2004	6.7-11.2
		2030 (1.5% increase/year)	9.4-15
Stampfl et al. (2007)	EU	Modeled harvestable yield	6.2-9.4
Vargas et al. (2002)	Denmark	1996 (drought)	3.4
		1997	5.9

Appendix Table 1-12: Stand length

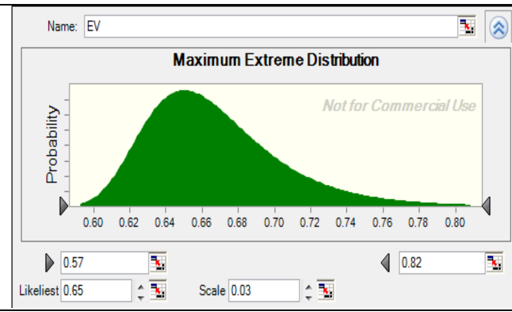
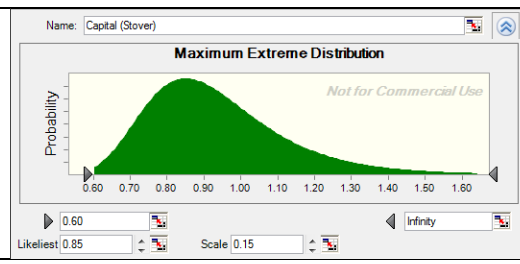
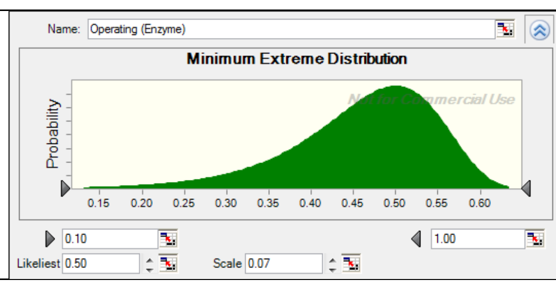
Feedstock	Length	Reference
Switchgrass	10 Years	Brechbill et al. (2008)
Switchgrass	10 Years	Duffy and Nanhou (2001)
Switchgrass	12 Years	Popp and Hogan (2007)
Switchgrass	20 Years	Tiffany et al. (2006)
Switchgrass	10 years	Khanna (2008)
Switchgrass	10 years	Khanna et al. (2008)
Switchgrass	10 years	Khanna and Dhungana (2007)
Switchgrass	10+ years	Lewandowski et al. (2003)
Switchgrass	10+ years	Fike et al. (2006)
Miscanthus	20 years	Khanna (2008)
Miscanthus	20 years	Khanna et al. (2008)
Miscanthus	20 years	Khanna and Dhungana (2007)
Miscanthus	20-25 years	Lewandowski et al. (2003)

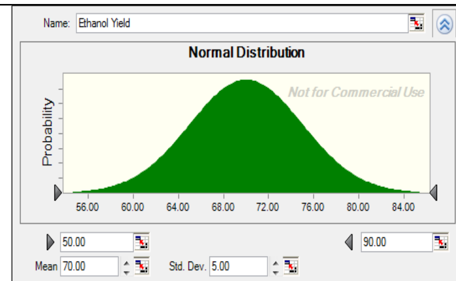
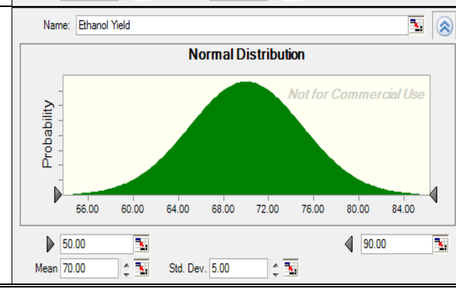
Appendix Table 1-13: Yield Maturity Rate

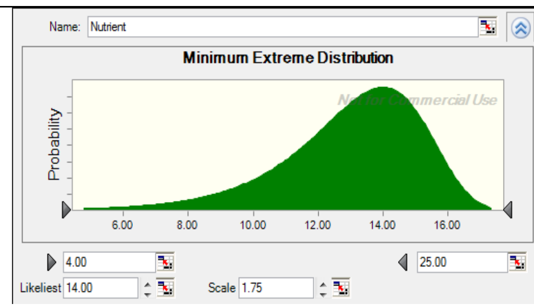
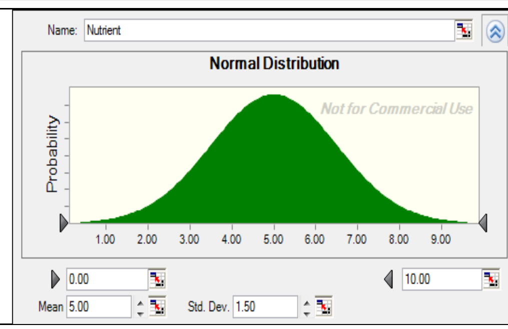
Feedstock	Year 1	Year 2	Year 3	Reference
Switchgrass	20-35%	60-75%	100%	Walsh (2008)
Switchgrass	No harvest			
Switchgrass	30%	67%	100%	Kszos et al. (2002)
Switchgrass	0	60%	100%	Popp and Hogan (2007)
Switchgrass	~33%	~66%	100%	McLaughlin and Kszos (2005)
Miscanthus		Full in warm climate	Full in cooler climate	Clifton-Brown et al. (2001)
Miscanthus	2-5 years for full			Heaton et al. (2004)
Miscanthus	Max at 4 years			Atkinson (2009)

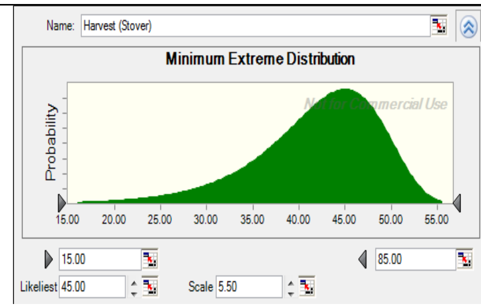
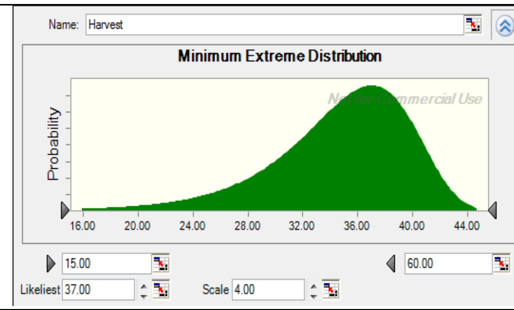
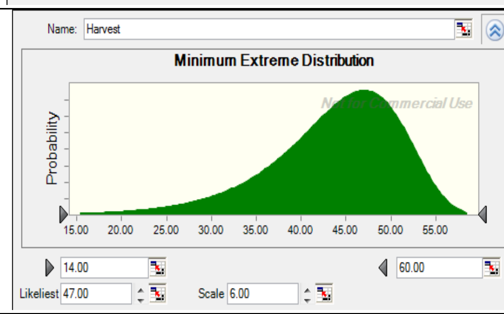
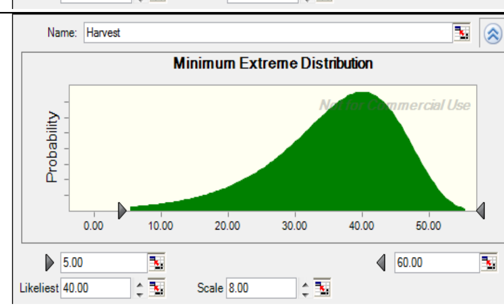
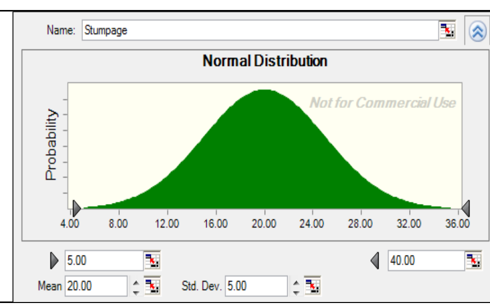
Appendix 2: Distribution Assumptions

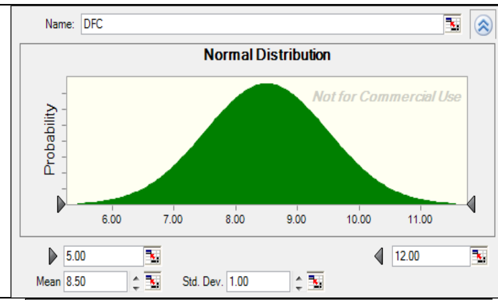
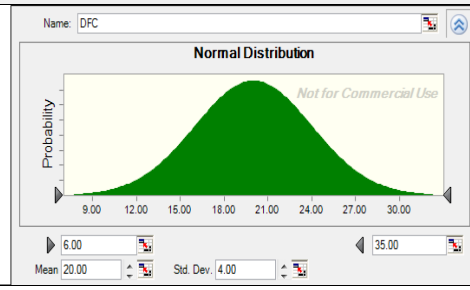
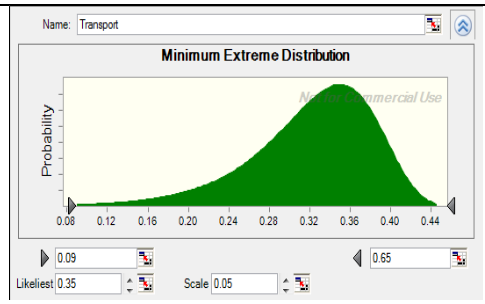
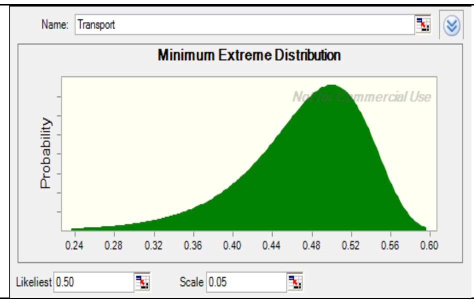
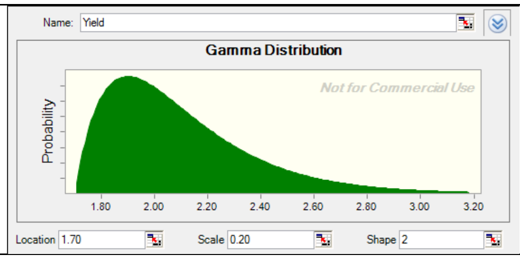
Appendix Table 2-1: Parameter Assumptions for Processor WTP

Parameter	Feedstock	Assumption	Distribution Figure
Oil Price (P_{Oil})	All	3 scenario levels	\$60 , \$75, \$90
EV	All	Truncated Maximum Extreme Min: 0.57 Likeliest: 0.65 Max: 0.82 Scale: 0.03 Mean: 0.67	
Tax (T)	All	\$1.01	
Byproduct value (V_{BP})	Stover	\$0.16	
	Switchgrass, *Miscanthus*, Wheat Straw, Prairie Grass	\$0.18	
	Aspen Wood	\$0.14	
Octane (V_O)	All	\$0.10	
Capital Cost (C_I)			
	All	Truncated Maximum Extreme Min: \$0.60 Likeliest: \$0.85 Scale: \$0.15 Mean: \$0.93	
Non-enzyme Operating Cost	All	\$0.36	
Enzyme Cost	All	Minimum Extreme Min: \$0.10 Likeliest: \$0.50 Max: \$1.00 Std. dev: \$0.07 Mean: \$0.46	

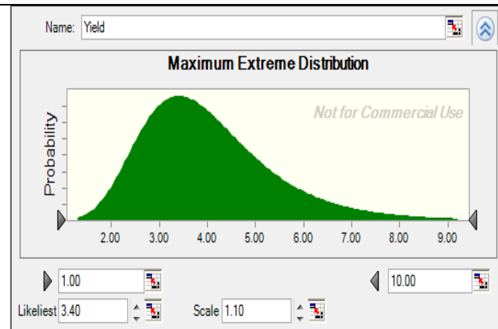
Yield (Y_E)	All - 2009	Normal Min: 50 Mean: 70 Max: 90 Std. dev: 5	
	All – 2020	Normal Min: 60 Mean: 80 Max: 100 Std. dev: 5	

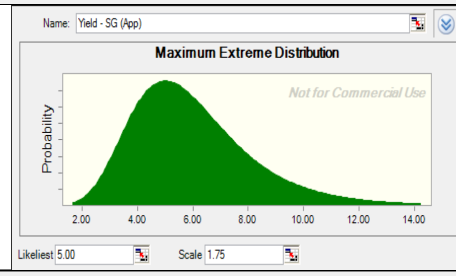
Appendix Table 2-2 – Parameter Assumptions for Supplier WTA			
Parameter	**Feedstock**	**Assumption**	**Distribution Figure**
Nutrient Replacement (C_{NR})			
	Stover, Switchgrass, *Miscanthus*, Prairie grass	Truncated Minimum Extreme Min: $4 Likeliest: $14 Max: $25 Scale: 1.75 Mean: $13	
	Wheat Straw	Normal Min: $0 Mean: $5 Max: $10 Std. Dev: 1.5	
Harvest and Maintenance (C_{HM})			

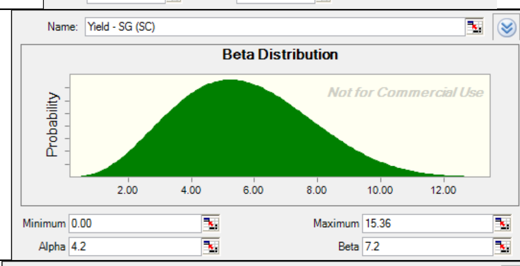
	Stover	Truncated Minimum Extreme Min: $15 Likeliest: $45 Max: $85 Scale: 5.5 Mean: $42	
	Switchgrass, Wheat Straw, Prairie grass	Truncated Minimum Extreme Min: $15 Likeliest: $37 Max: $60 Scale: 4 Mean: $35	
	Miscanthus	Truncated Minimum Extreme Min: $14 Likeliest: $47 Max: $60 Scale: 6 Mean: $44	
	Aspen Wood	Truncated Minimum Extreme Min: $5 Likeliest: $40 High:$60 Scale: 8 Mean: $36	
Stumpage Fee (SF)	Aspen Wood	Normal Min: $5 Mean: $20 Max: $40 Std dev: $5	
Distance Fixed Cost (DFC)			

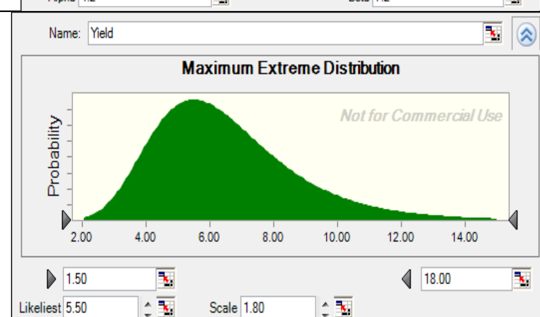
	Stover, Switchgrass, *Miscanthus*, Wheat Straw, Prairie Grass	Normal Min: \$5 Mean: \$8.50 Max: \$12 Std. Dev: 1	
	Aspen Wood (includes chipping)	Normal Min: \$6 Mean: \$20 Max: \$35 Std Dev: 4	
Distance Variable Cost (DVC)			
	Stover, Switchgrass, *Miscanthus*, Wheat Straw, Prairie Grass	Truncated Minimum Extreme Min: \$0.09 Likeliest: \$0.35 Max: \$0.65 Scale: 0.05 Mean: \$0.32	
	Aspen Wood	Minimum Extreme Likeliest: \$0.50 Scale: \$0.05 Mean: \$0.47	
Annual Biomass Demand (BD)	All	77,1750 tons (2,205 t/day) (350 days/year)	
Yield (Y_B)			
	Stover	Gamma Location: 1.70 Scale: 0.20 Shape: 2 Mean: 2.1	

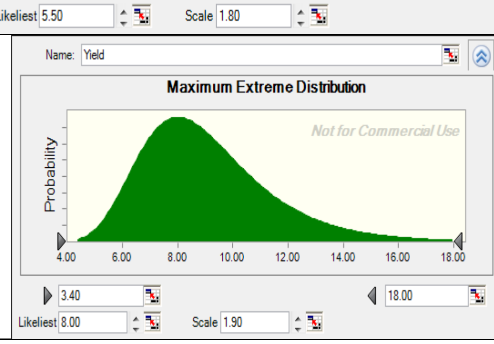
<table>
<tr><td></td><td>Switchgrass
(Midwest)</td><td>Truncated
Maximum
Extreme

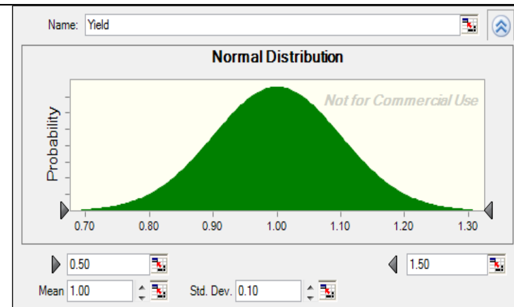
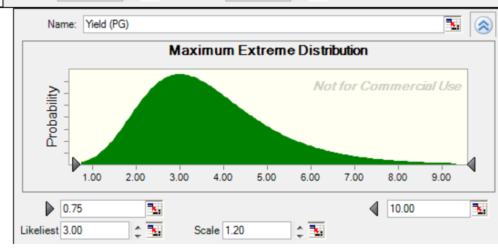
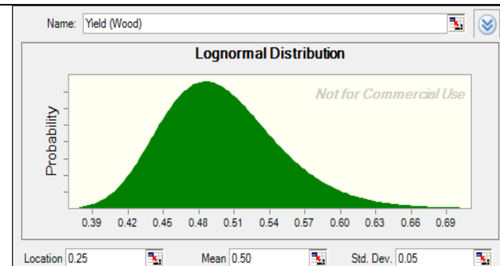
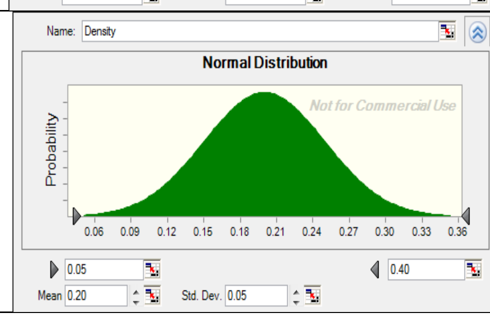
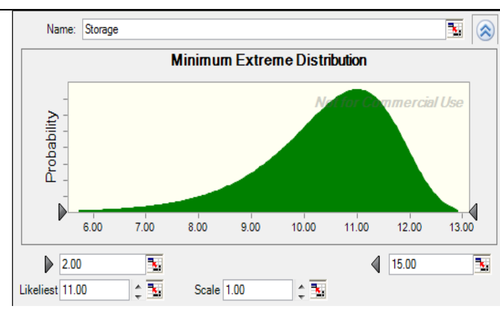
Min: 1
Likeliest: 3.4
Max: 10
Scale: 1.1
Mean: 4</td><td>
</td></tr>
<tr><td></td><td>Switchgrass
(Appalachian)</td><td>Truncated
Maximum
Extreme

Likeliest: 5
Scale: 1.75
Mean: 6</td><td>
</td></tr>
<tr><td></td><td>Switchgrass
(South-
Central)</td><td>Beta

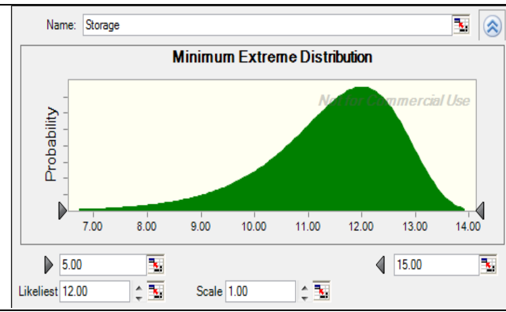
Min: 0
Alpha: 4.2
Beta: 7.2
Max: 15.36
Mean: 5.70</td><td>
</td></tr>
<tr><td></td><td>Miscanthus
(Midwest)</td><td>Truncated
Maximum
Extreme

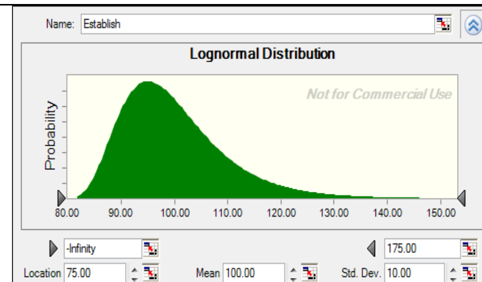
Min: 1.5
Likeliest: 5.5
Max: 18
Scale: 1.8
Mean: 6.5</td><td>
</td></tr>
<tr><td></td><td>Miscanthus
(Appalachian)</td><td>Truncated
Maximum
Extreme

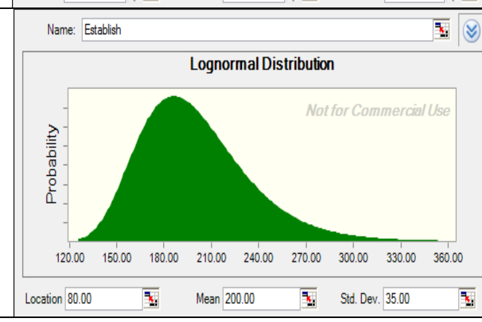
Min: 3.4
Likeliest: 8
Max: 18
Scale: 1.9
Mean: 9</td><td>
</td></tr>
</table>

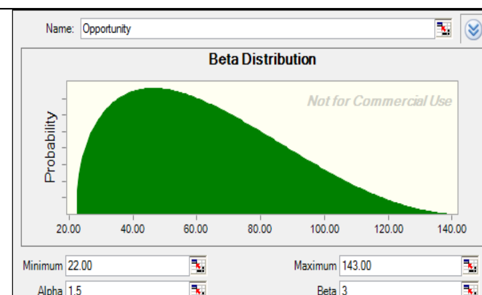
	Wheat Straw	Normal Min: 0.5 Mean: 1 Max: 1.5 Std. Dev: 0.10	
	Prairie Grass	Maximum Extreme Min: 0.75 Likeliest: 3.00 Max: 10 Scale: 1.20 Mean: 3.6	
	Aspen Wood	Normal Location: 0.25 Mean: 0.50 Std. dev: 0.05	
Biomass Density (B)	All	Normal Min: 0.05 Mean: 0.20 Max: 0.40 Std Dev: 0.05	
Storage (C_S)			
	Stover, Switchgrass, *Miscanthus*, Wheat Straw, Prairie Grass	Truncated Minimum Extreme Min: \$2 Likeliest: \$11 Max: \$15 Scale: 1 Mean: \$10.50	

<table>
<tr><td></td><td>Aspen Wood</td><td>Truncated Minimum Extreme

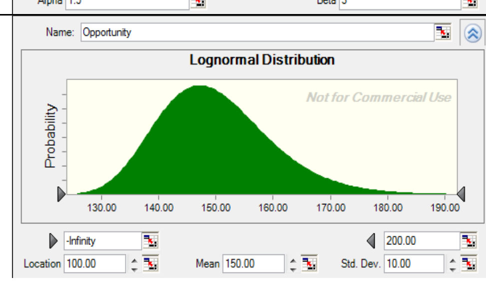
Min: $5
Likeliest: $12
Max: $15
Scale: 1
Mean: $11.50</td><td>
</td></tr>
<tr><td>Establishment and Seeding (C_{ES})</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Switchgrass, Prairie Grass</td><td>Lognormal

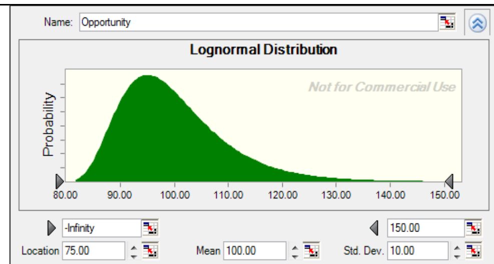
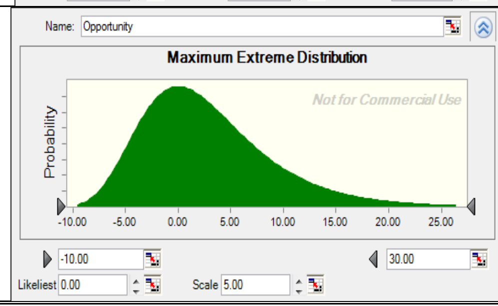
Location: $75
Mean: $100
Max: $175
Std. Dev: 10</td><td>
</td></tr>
<tr><td></td><td>Miscanthus</td><td>Lognormal

Location: $80
Mean: $200
St. Dev: $35</td><td>
</td></tr>
<tr><td>Opportunity Cost (C_{Opp})</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Stover</td><td>Beta

Min: $22
Max: $143
Alpha: 1.5
Beta: 3
Mean: $62</td><td>
</td></tr>
<tr><td></td><td>Switchgrass, Miscanthus (Midwest)</td><td>Lognormal Distribution

Location: $100
Mean: $150
Max: $200
Scale: 10

0.75 Correlation with Stover Yield</td><td>
</td></tr>
</table>

	Switchgrass, *Miscanthus* (Appalachian, South Central), Prairie Grass	Lognormal Distribution Location: $75 Mean: $100 Max: $150 Std. Dev: 10		
	Wheat Straw	Maximum Extreme Min: -$10 Likeliest: $0 Max: $30 Scale: 5 Mean: $2.6		

Appendix 3: Additional Simulation Results

Appendix Table 3-1. Mean MWTP, MWTA and Difference (Δ) by Oil Price with 70 gal/ton Conversion
No Producer's Credit or CHST Payment

	MWTP			MWTA	Difference (Δ)		
Oil Price	**$60**	**$75**	**$90**	**--**	**$60**	**$75**	**$90**
Corn Stover	-$9	$15	$39	$113	-$122	-$97	-$73
Switchgrass (MW)	-$7	$18	$42	$142	-$148	-$124	-$100
Switchgrass (App)	-$7	$18	$42	$110	-$117	-$92	-$68
Switchgrass (SC)	-$7	$18	$42	$116	-$122	-$98	-$74
Miscanthus (MW)	-$7	$18	$42	$141	-$148	-$124	-$100
Miscanthus (App)	-$7	$18	$42	$115	-$122	-$98	-$73
Wheat Straw	-$7	$18	$42	$74	-$81	-$56	-$32
Prairie Grass	-$7	$18	$42	$139	-$145	-$121	-$97
Woody Biomass	-$10	$14	$38	$113	-$124	-$99	-$75

Appendix Table 3-2. Mean MWTP, MWTA and Difference (Δ) by Oil Price with 80/gal ton Conversion
No Producer's Credit or CHST Payment

	MWTP			MWTA	Difference (Δ)		
Oil Price	**$60**	**$75**	**$90**	**--**	**$60**	**$75**	**$90**
Corn Stover	-$10	$17	$45	$113	-$123	-$95	-$68
Switchgrass (MW)	-$7	$20	$48	$142	-$149	-$122	-$94
Switchgrass (App)	-$7	$20	$48	$110	-$117	-$90	-$62
Switchgrass (SC)	-$7	$20	$48	$116	-$123	-$95	-$68
Miscanthus (MW)	-$7	$20	$48	$141	-$149	-$121	-$94
Miscanthus (App)	-$7	$20	$48	$115	-$123	-$95	-$67
Wheat Straw	-$7	$20	$48	$74	-$82	-$54	-$26
Prairie Grass	-$7	$20	$48	$139	-$146	-$119	-$91
Woody Biomass	-$12	$16	$43	$113	-$125	-$97	-$70

Appendix Table 3-3. Mean MWTP, MWTA and Difference (Δ) by Oil Price with 70 gal/ton Conversion
Producer's Credit Only

	MWTP			MWTA	Difference (Δ)		
Oil Price	**$60**	**$75**	**$90**	**--**	**$60**	**$75**	**$90**
Corn Stover	$62	$86	$110	$112	-$51	-$27	-$3
Switchgrass (MW)	$64	$88	$112	$142	-$78	-$54	-$30
Switchgrass (App)	$64	$88	$112	$110	-$46	-$22	**$2**
Switchgrass (SC)	$64	$88	$112	$115	-$50	-$26	-$2
Miscanthus (MW)	$64	$88	$112	$140	-$76	-$52	-$28
Miscanthus (App)	$64	$88	$112	$115	-$51	-$27	-$3
Wheat Straw	$64	$88	$112	$74	-$10	**$14**	**$38**
Prairie Grass	$64	$88	$112	$139	-$75	-$50	-$26
Woody Biomass	$61	$85	$109	$113	-$52	-$28	-$4

Appendix Table 3-4. Mean MWTP, MWTA and Difference (Δ) by Oil Price with 80/gal ton Conversion Producer's Credit Only							
	MWTP			MWTA	Difference (Δ)		
Oil Price	**$60**	**$75**	**$90**	**--**	**$60**	**$75**	**$90**
Corn Stover	$70	$98	$126	$112	-$42	-$14	**$13**
Switchgrass (MW)	$74	$101	$129	$142	-$69	-$41	-$14
Switchgrass (App)	$74	$101	$129	$110	-$37	-$9	**$18**
Switchgrass (SC)	$74	$101	$129	$115	-$41	-$14	**$14**
Miscanthus (MW)	$74	$101	$129	$140	-$67	-$39	-$12
Miscanthus (App)	$74	$101	$129	$115	-$42	-$14	**$14**
Wheat Straw	$74	$101	$129	$74	-$1	**$27**	**$54**
Prairie Grass	$74	$101	$129	$139	-$65	-$38	-$10
Woody Biomass	$70	$98	$125	$113	-$43	-$15	**$12**

Appendix Table 3-5. Mean MWTP, MWTA and Difference (Δ) by Oil Price with 70 gal/ton Conversion Producer's Credit and CHST Payment							
	MWTP			MWTA	Difference (Δ)		
Oil Price	**$60**	**$75**	**$90**	**--**	**$60**	**$75**	**$90**
Corn Stover	$63	$87	$111	$68	-$5	**$19**	**$43**
Switchgrass (MW)	$63	$88	$112	$97	-$34	-$10	**$15**
Switchgrass (App)	$63	$88	$112	$65	-$2	**$22**	**$47**
Switchgrass (SC)	$63	$88	$112	$72	-$9	**$15**	**$39**
Miscanthus (MW)	$63	$88	$112	$96	-$32	-$8	**$16**
Miscanthus (App)	$63	$88	$112	$71	-$7	**$17**	**$41**
Wheat Straw	$63	$88	$112	$29	**$34**	**$58**	**$82**
Prairie Grass	$63	$88	$112	$93	-$30	-$6	**$19**
Woody Biomass	$61	$85	$109	$69	-$8	**$17**	**$41**

Appendix Table 3-6. Mean MWTP, MWTA and Difference (Δ) by Oil Price with 80/gal ton Conversion Producer's Credit and CHST Payment							
	MWTP			MWTA	Difference (Δ)		
Oil Price	**$60**	**$75**	**$90**	**--**	**$60**	**$75**	**$90**
Corn Stover	$71	$99	$126	$68	**$3**	**$31**	**$58**
Switchgrass (MW)	$72	$100	$127	$97	-$25	**$3**	**$30**
Switchgrass (App)	$72	$100	$127	$65	**$7**	**$35**	**$62**
Switchgrass (SC)	$72	$100	$127	$72	**$0**	**$27**	**$55**
Miscanthus (MW)	$72	$100	$127	$96	-$23	**$4**	**$32**
Miscanthus (App)	$72	$100	$127	$71	**$2**	**$29**	**$57**
Wheat Straw	$72	$100	$127	$29	**$43**	**$70**	**$98**
Prairie Grass	$72	$100	$127	$93	-$21	**$7**	**$34**
Woody Biomass	$69	$97	$125	$69	**$1**	**$28**	**$56**

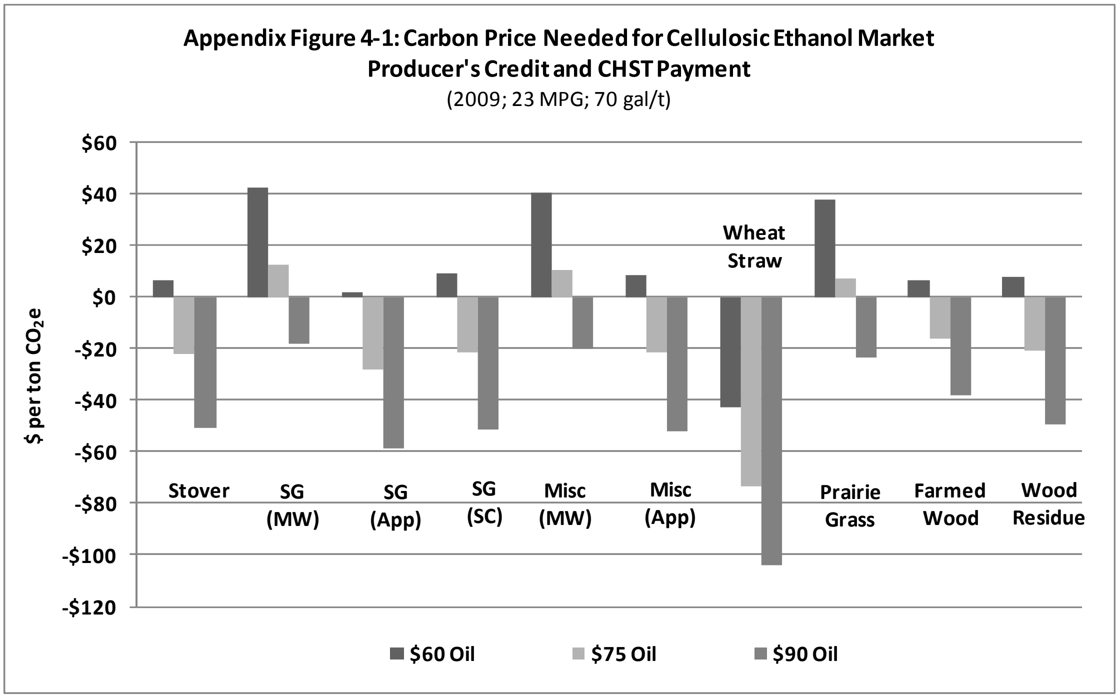
Appendix Table 3-7 – Simulated Mean Difference (Δ) at the Baseline Oil Price (80 gal/ton Conversion)			
	No Credit or Payment	**Credit Only**	**Credit and Payment**
Corn Stover	-$95	-$14	**$31**
Switchgrass (MW)	-$122	-$41	**$3**
Switchgrass (App)	-$90	-$9	**$35**
Switchgrass (SC)	-$95	-$14	**$27**
Miscanthus (MW)	-$121	-$39	**$4**
Miscanthus (App)	-$95	-$14	**$29**
Wheat Straw	-$54	**$27**	**$70**
Prairie Grass	-$119	-$38	**$7**
Woody Biomass	-$97	-$15	**$28**

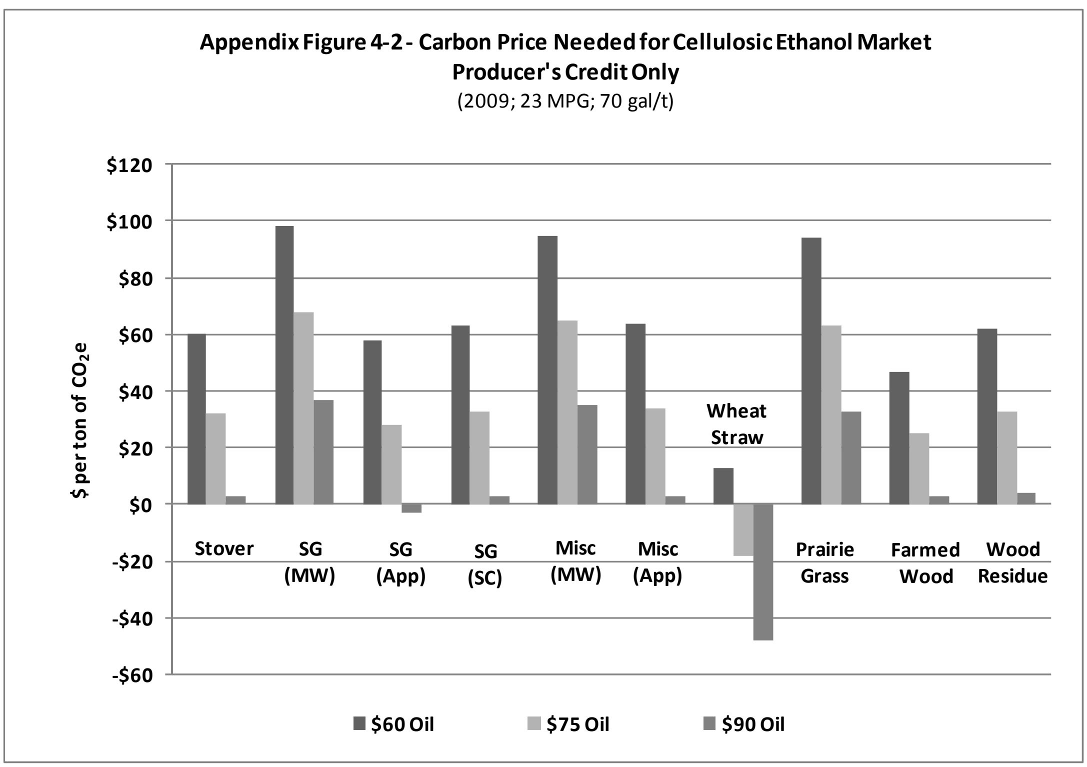
Appendix Table 3-8 – 90% Confidence Interval for the Difference (Δ) at the Baseline Oil Price (80 gal/ton Conversion)			
	No Credit or Payment	**Credit Only**	**Credit and Payment**
Corn Stover	-135, -59	**-55, 26**	**-12, 70**
Switchgrass (MW)	-180, -75	**-100, 6**	**-52, 50**
Switchgrass (App)	-134, -50	**-57, 31**	**-8, 72**
Switchgrass (SC)	-152, -52	**-72, 31**	**-32, 72**
Miscanthus (MW)	-174, -77	**-92, 5**	**-50, 48**
Miscanthus (App)	-134, -59	**-54, 24**	**-11, 67**
Wheat Straw	-89, -21	**-9, 60**	**36, 104**
Prairie Grass	-186, -67	**-104, 16**	**-57, 56**
Woody Biomass	-136, -61	**-55, 21**	**-10, 64**

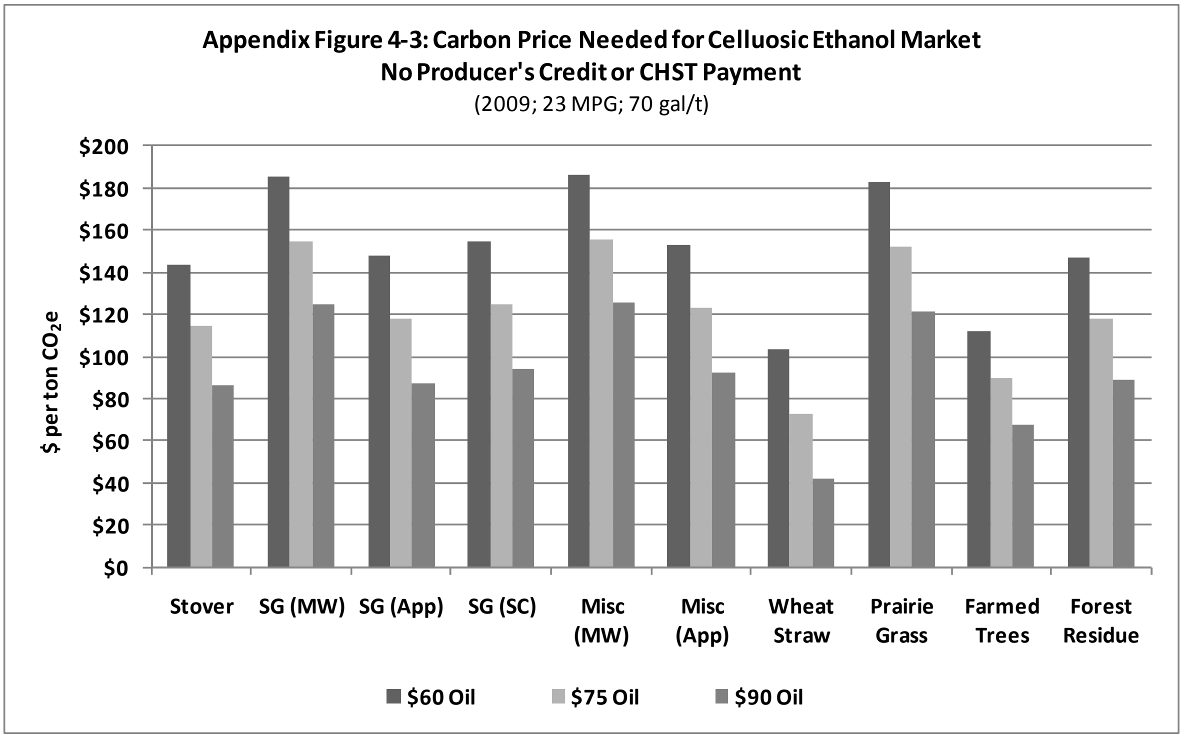
Appendix Table 3-9 - Carbon Credit Necessary for Cellulosic Ethanol Market Producer's Credit Only												
	2009 (23 MPG, 70)			2009 (32 MPG)			2020 (32 MPG, 80)			2020 (41 MPG)		
Oil Price	**$60**	**$75**	**$90**	**$60**	**$75**	**$90**	**$60**	**$75**	**$90**	**$60**	**$75**	**$90**
Corn Stover	$60	$32	$3	$42	$22	$2	$33	$11	**-$11**	$25	$9	**-$8**
SG (MW)	$98	$68	$37	$67	$47	$26	$57	$34	$11	$43	$26	$8
SG (App)	$58	$28	**-$3**	$40	$19	**-$2**	$30	$8	**-$15**	$23	$6	**-$11**
SG (SC)	$63	$33	$3	$43	$23	$2	$34	$11	**-$12**	$26	$8	-$9
Mis (MW)	$95	$65	$35	$66	$45	$24	$55	$32	$10	$41	$24	$7
Mis (App)	$64	$34	$3	$44	$23	$2	$34	$12	**-$11**	$26	$9	**-$8**
Wheat S	$13	**-$18**	**-$48**	$9	**-$12**	**-$33**	$1	**-$22**	**-$45**	$0	**-$17**	**-$34**
Prairie Grass	$94	$63	$33	$64	$44	$23	$54	$31	$8	$41	$23	$6
Farmed Trees	$47	$25	$3	$35	$19	$2	$28	$10	**-$8**	$22	$8	**-$6**
Forest Residue	$62	$33	$4	$43	$23	$3	$33	$12	**-$9**	$25	$9	**-$7**

Appendix 4: Additional Sensitivity Results

A. Oil Price and Policy Incentive



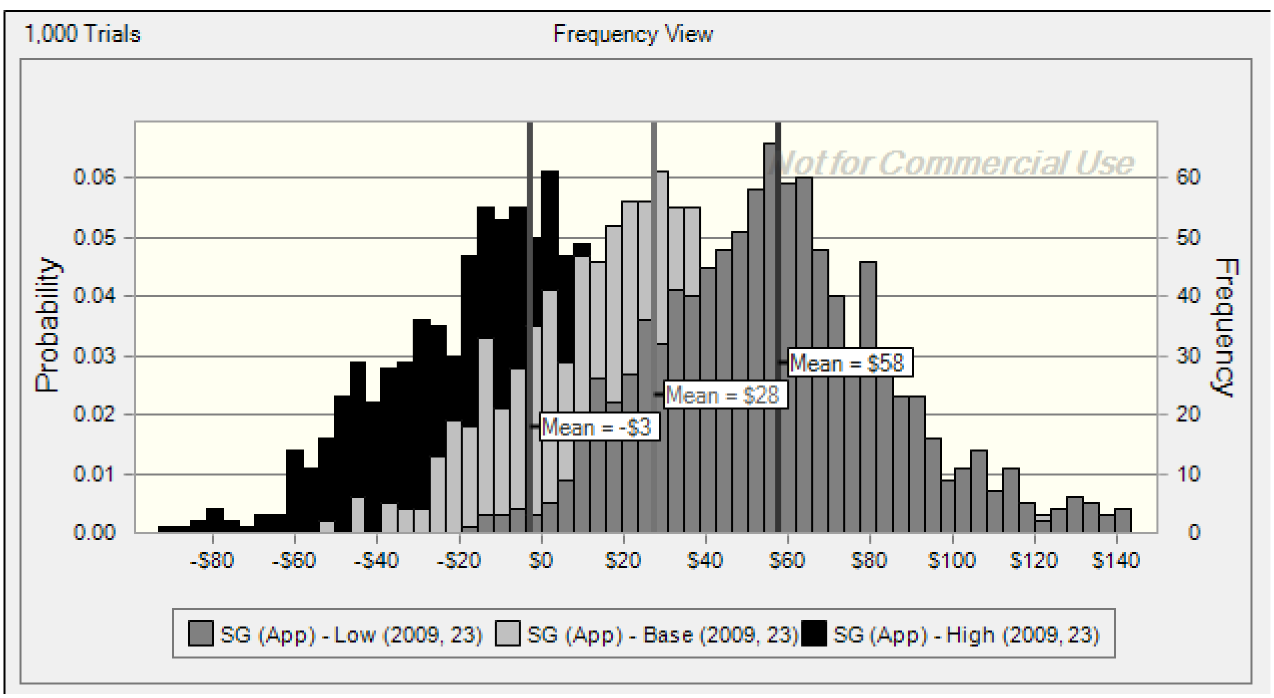




Appendix Figure 4-4 - Simulation for the Carbon Price to Sustain a Switchgrass Market by Oil Price

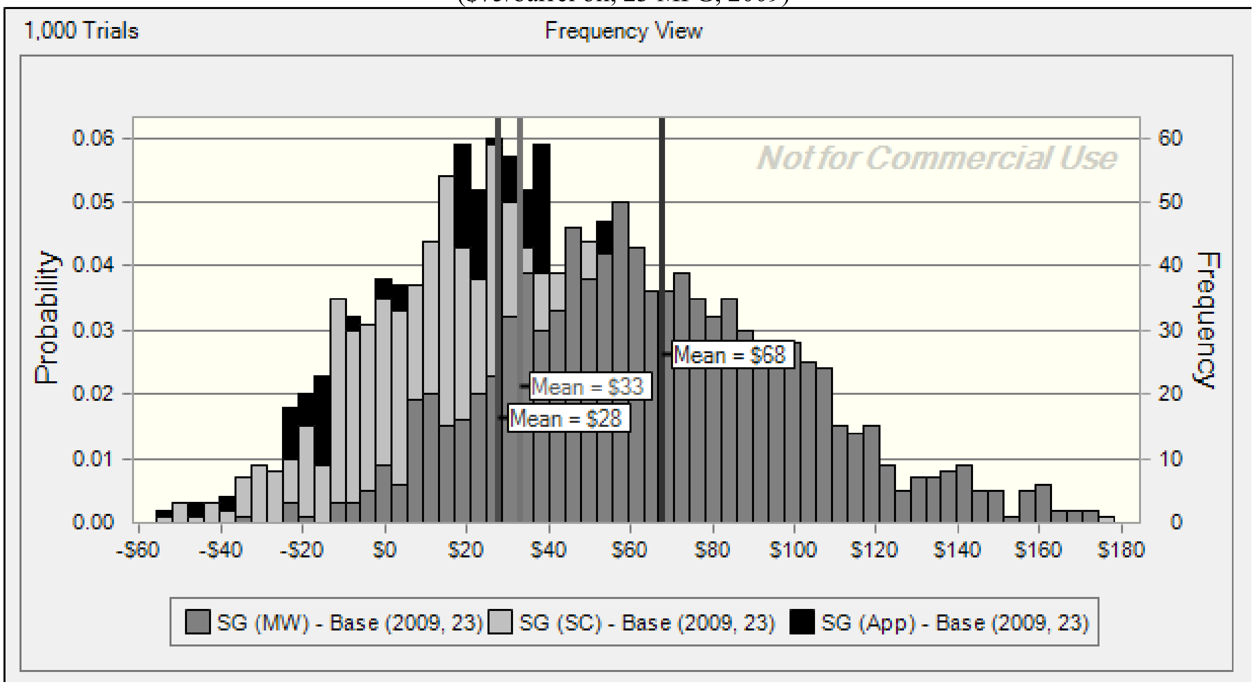
Producer's Credit Only

(23 MPG, 2009, Appalachian Region)

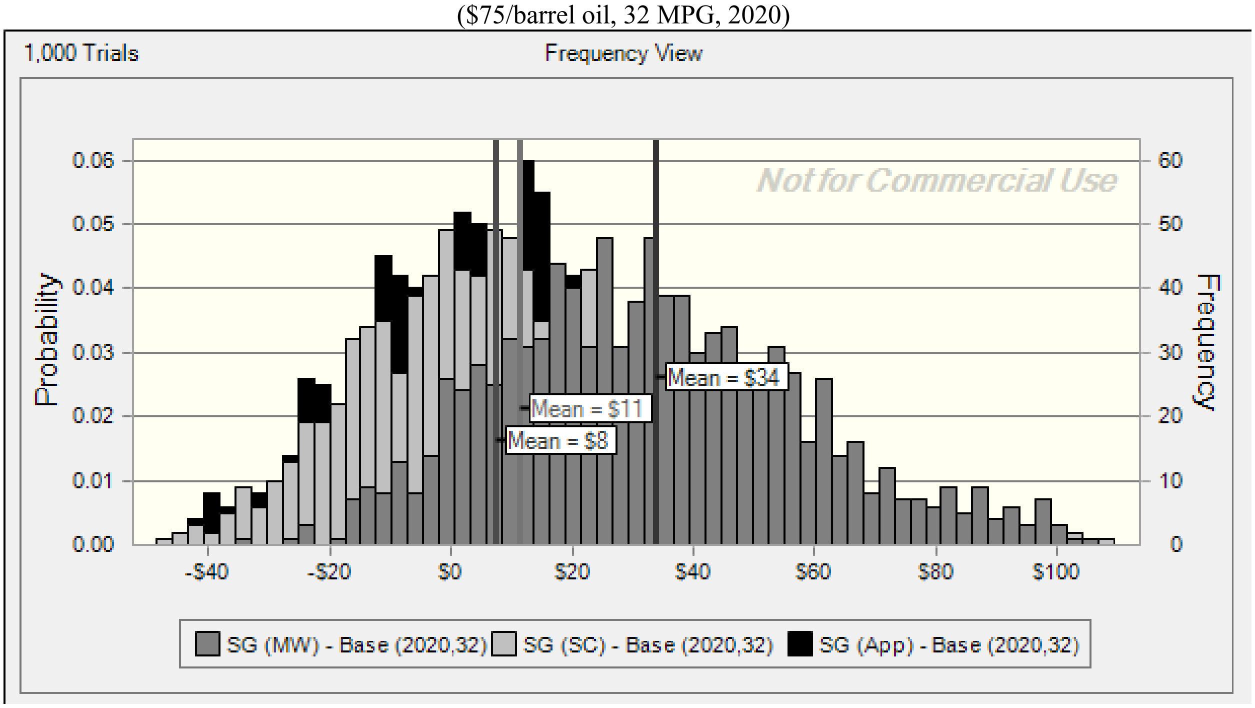


B. Regional Variation

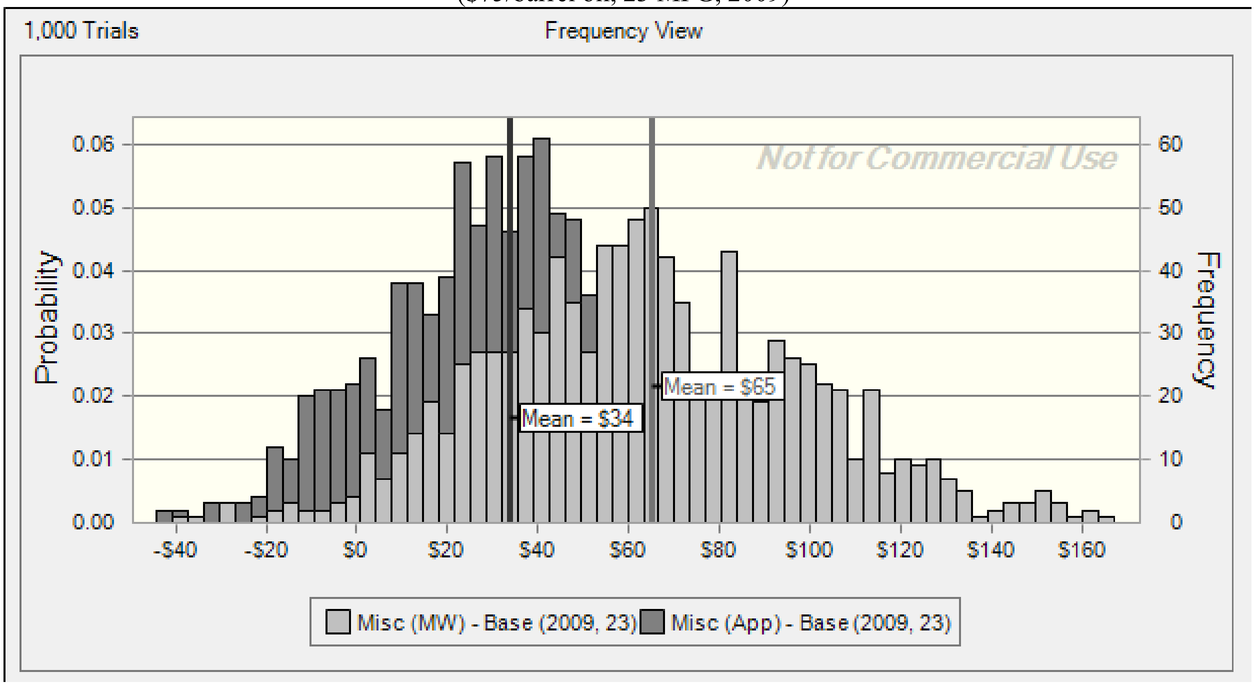
Appendix Figure 4-5 - Simulation for Carbon Price Needed to Sustain a Switchgrass Market by Region
Producer's Credit Only
($75/barrel oil, 23 MPG, 2009)



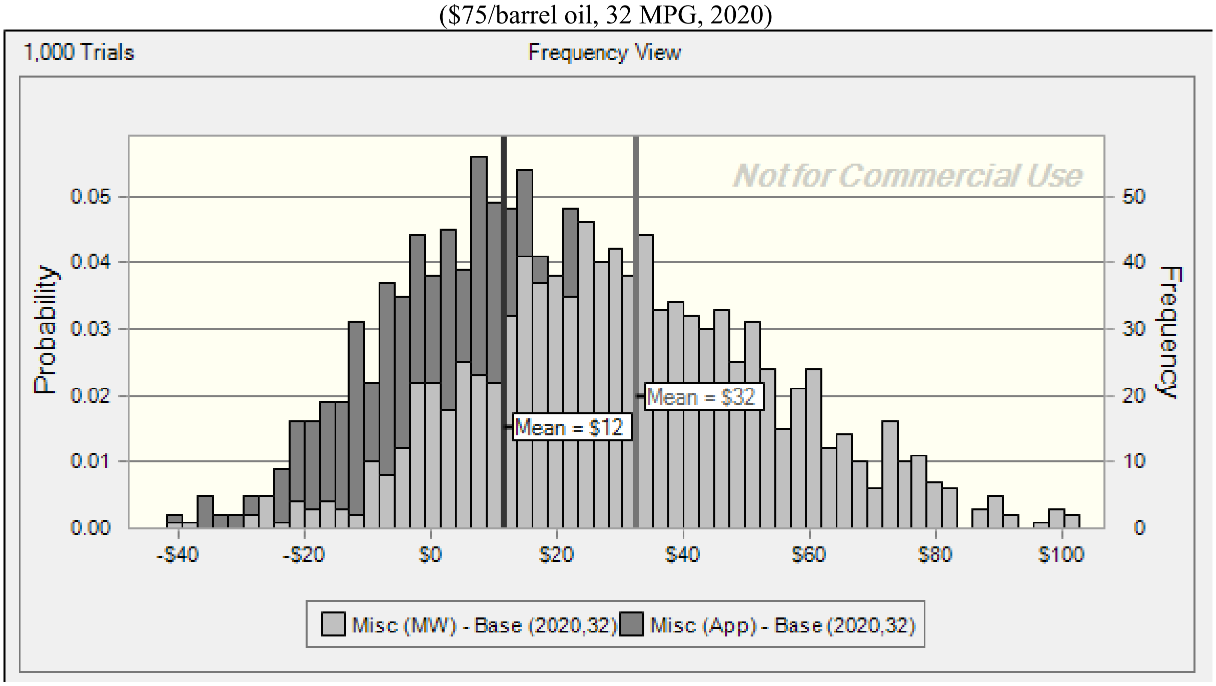
Appendix Figure 4-6 - Simulation for Carbon Price Needed to Sustain a Switchgrass Market by Region
Producer's Credit Only
($75/barrel oil, 32 MPG, 2020)



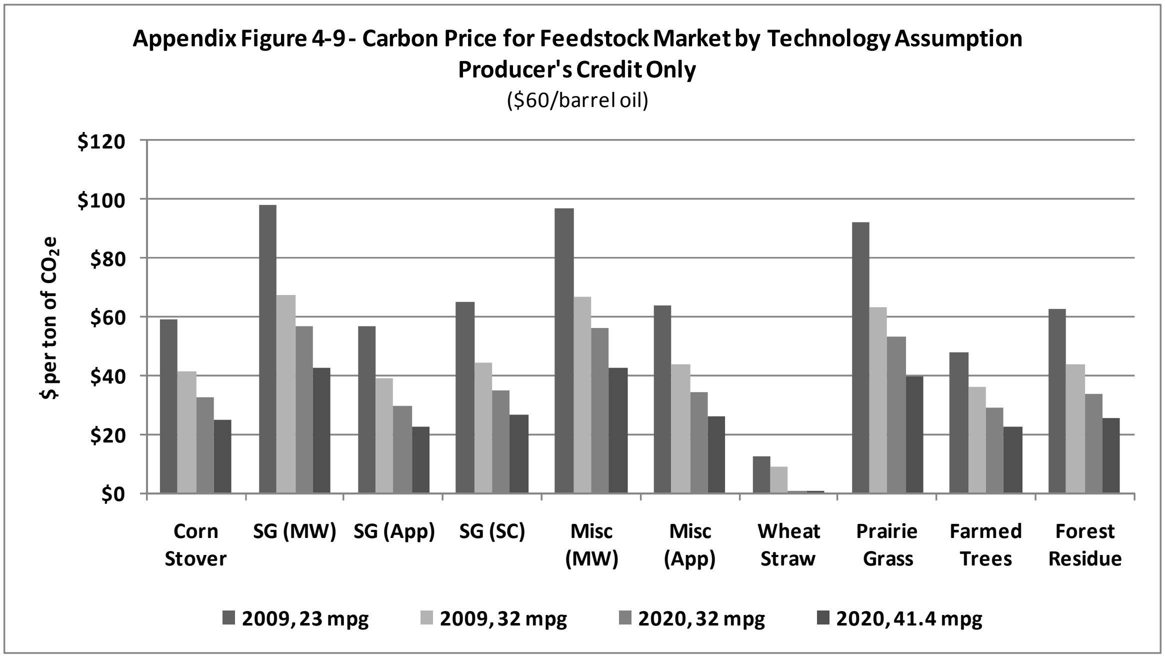
Appendix Figure 4-7 - Simulation for Carbon Price Needed to Sustain a Miscanthus Market by Region
Producer's Credit Only
($75/barrel oil, 23 MPG, 2009)



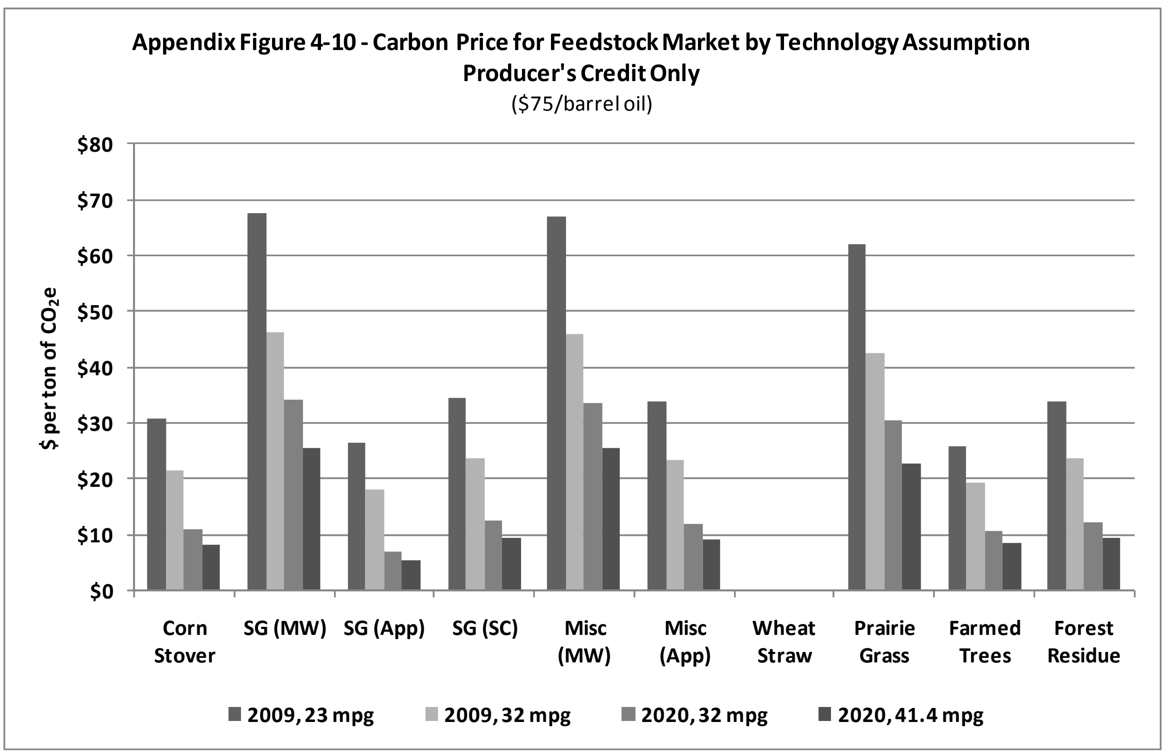
Appendix Figure 4-8 - Simulation for Carbon Price Needed to Sustain a Miscanthus Market by Region
Producer's Credit Only
($75/barrel oil, 32 MPG, 2020)



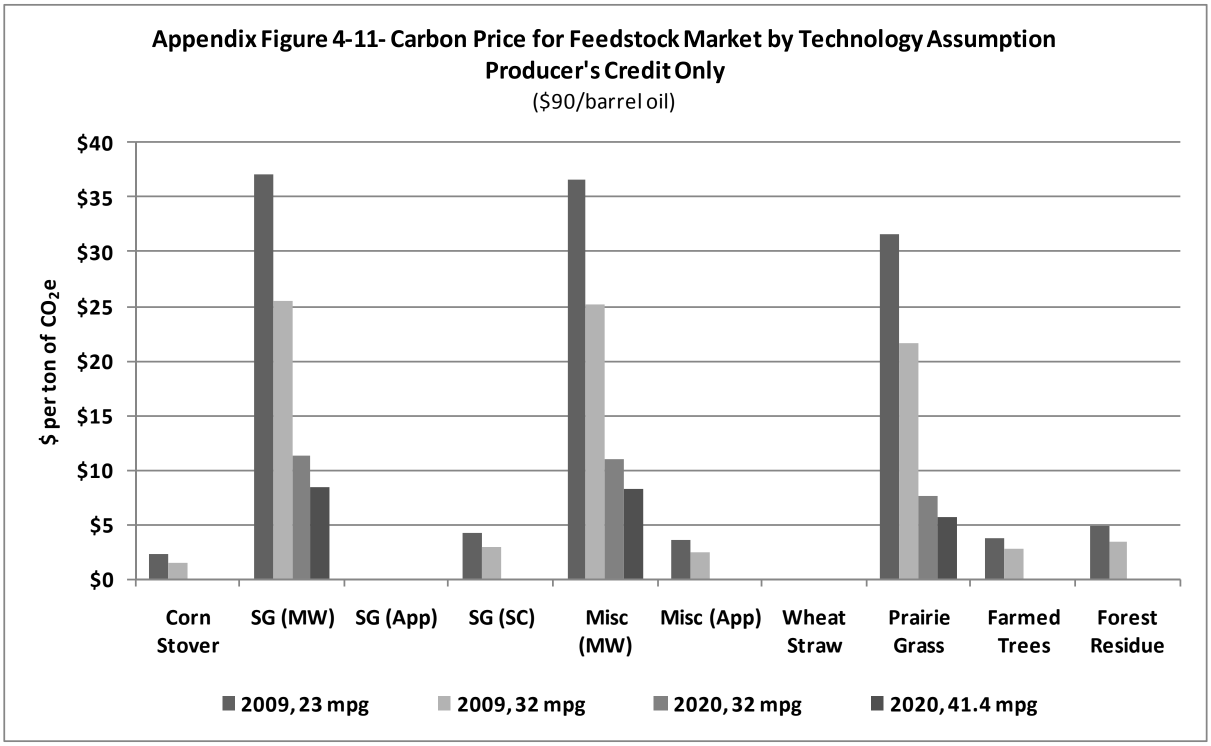
C. Technology Advancement



* 70 gallons per ton conversion assumed for 2009 technology
* 80 gallons per ton conversion assumed for 2020 technology

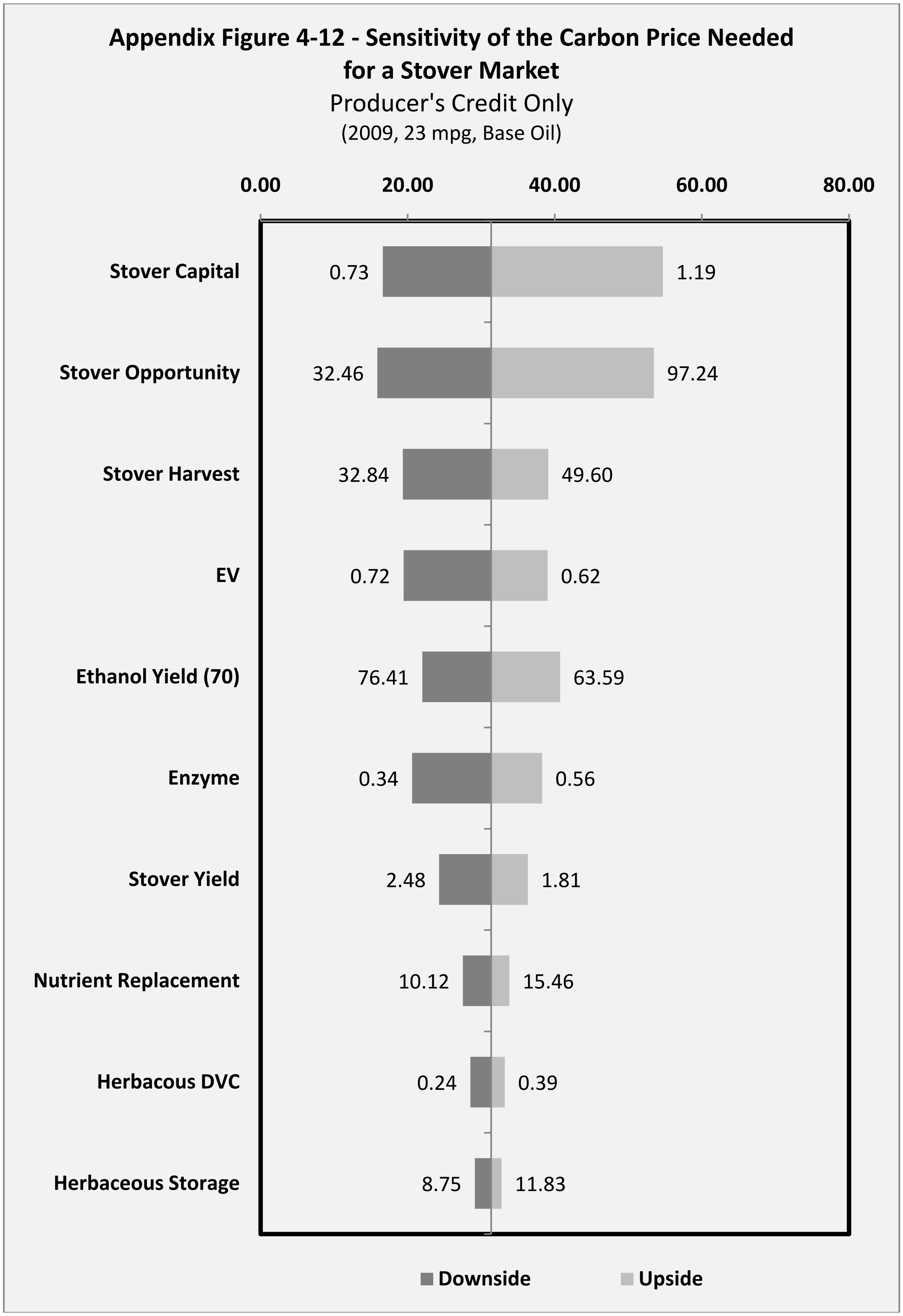


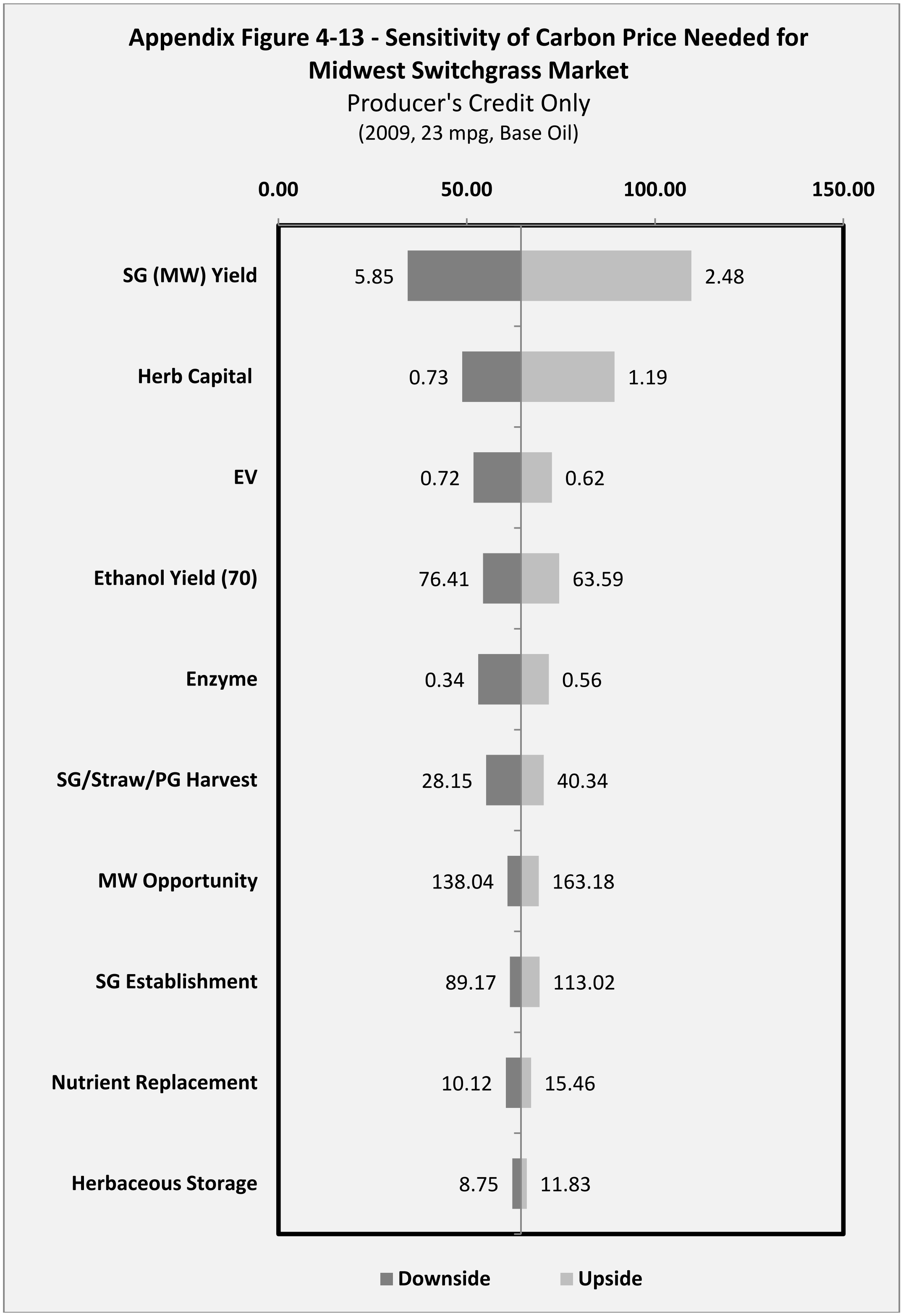
* 70 gallons per ton conversion assumed for 2009 technology
* 80 gallons per ton conversion assumed for 2020 technology



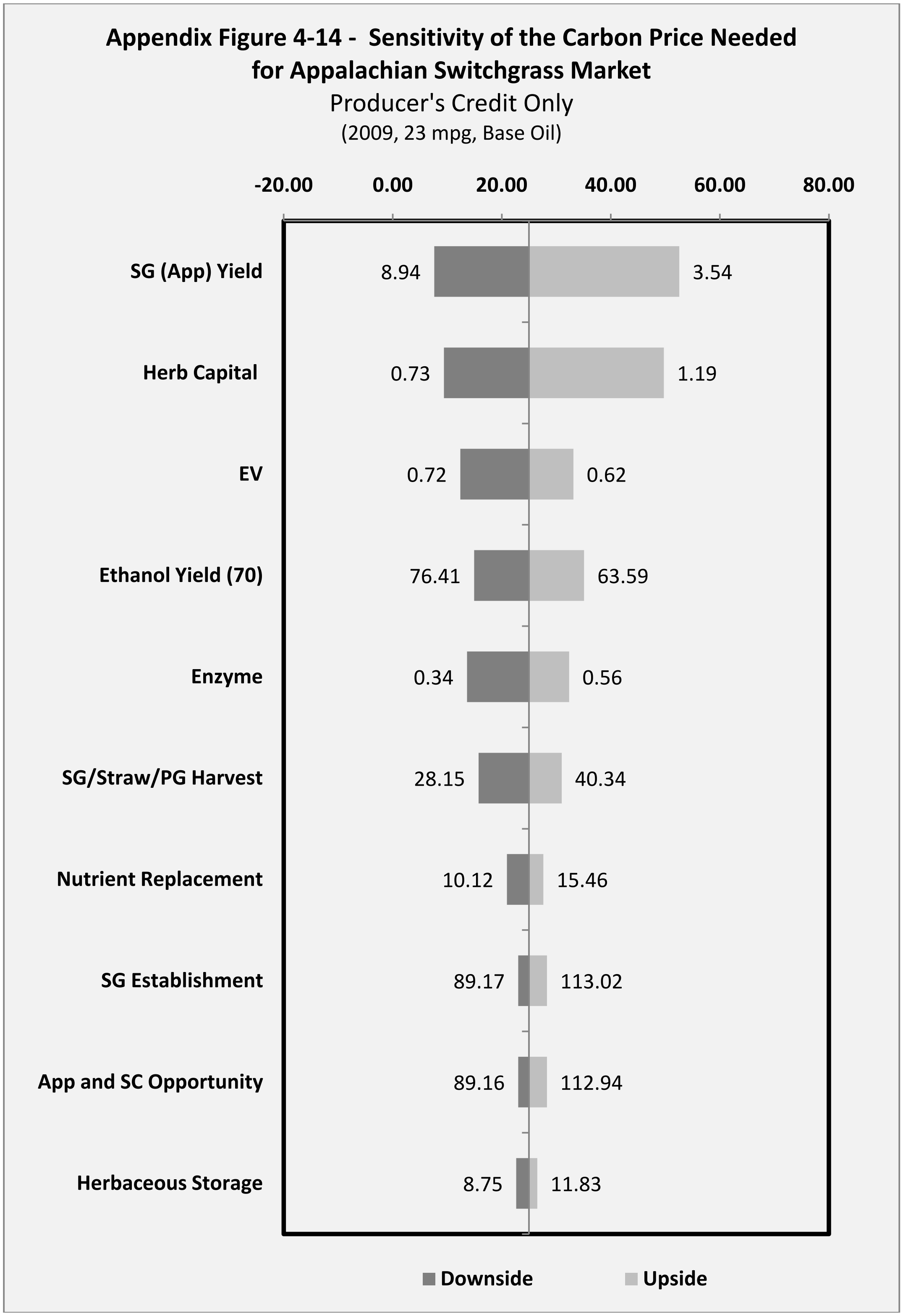
* 70 gallons per ton conversion assumed for 2009 technology
* 80 gallons per ton conversion assumed for 2020 technology

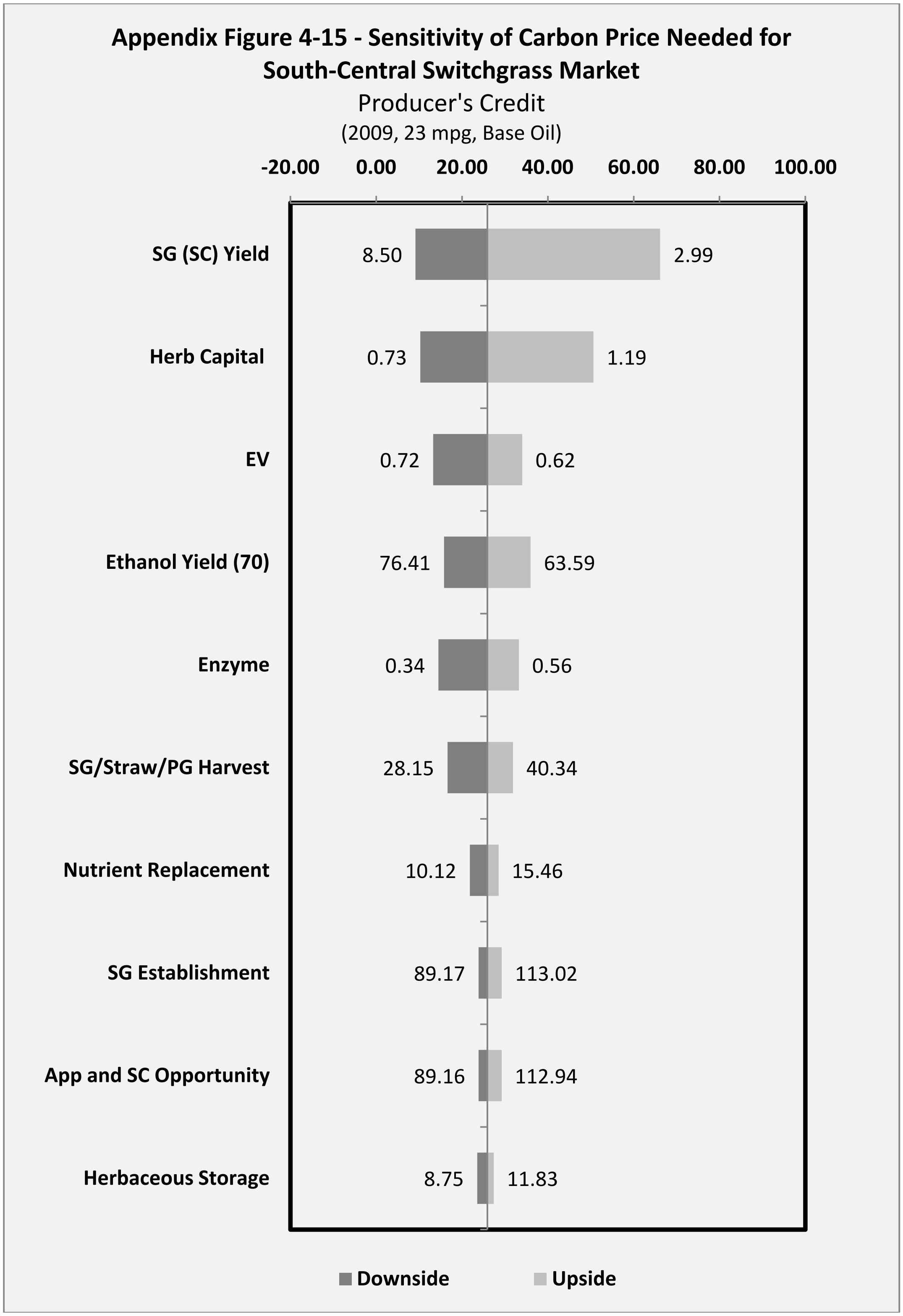
D. Parameter Variability

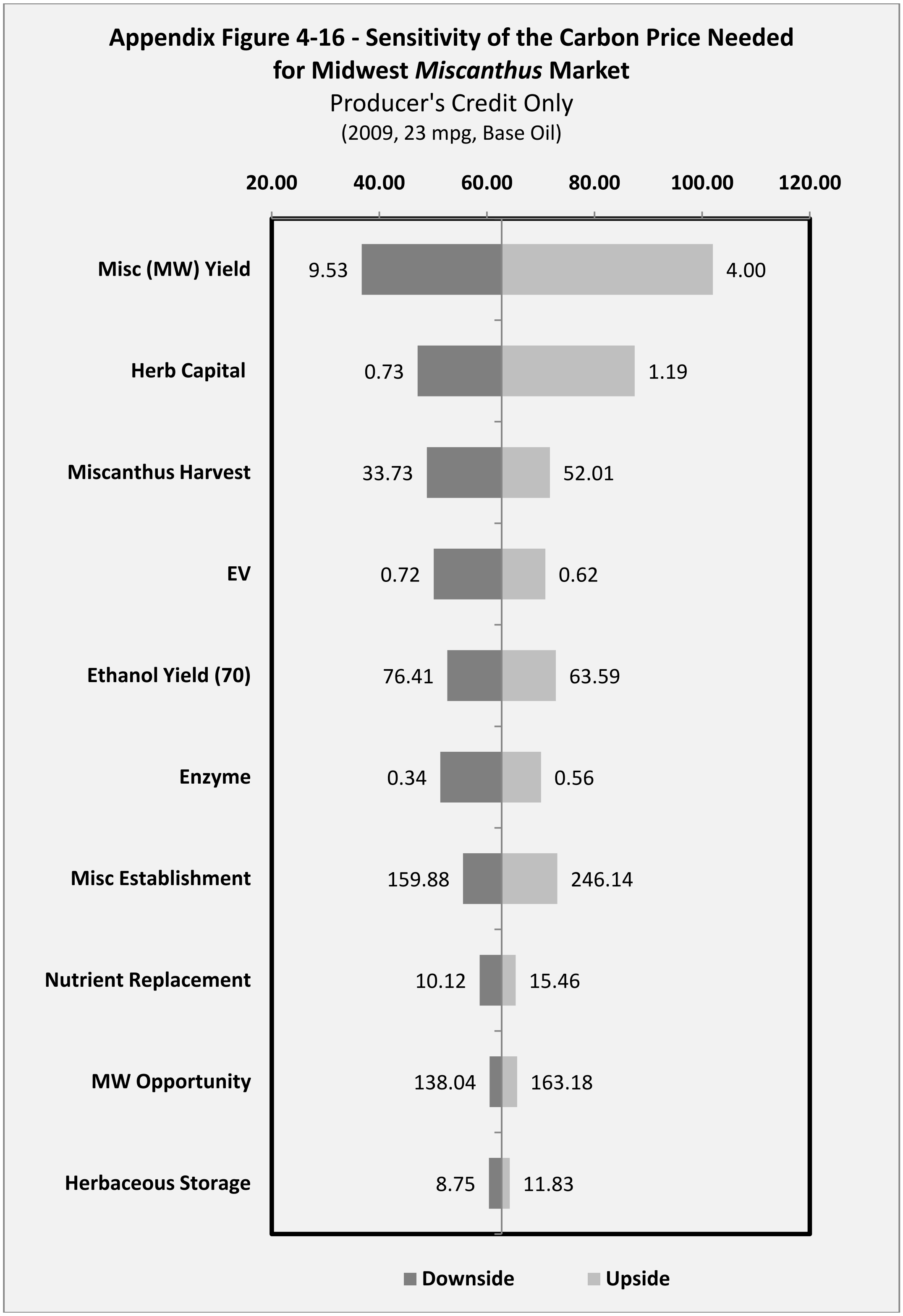




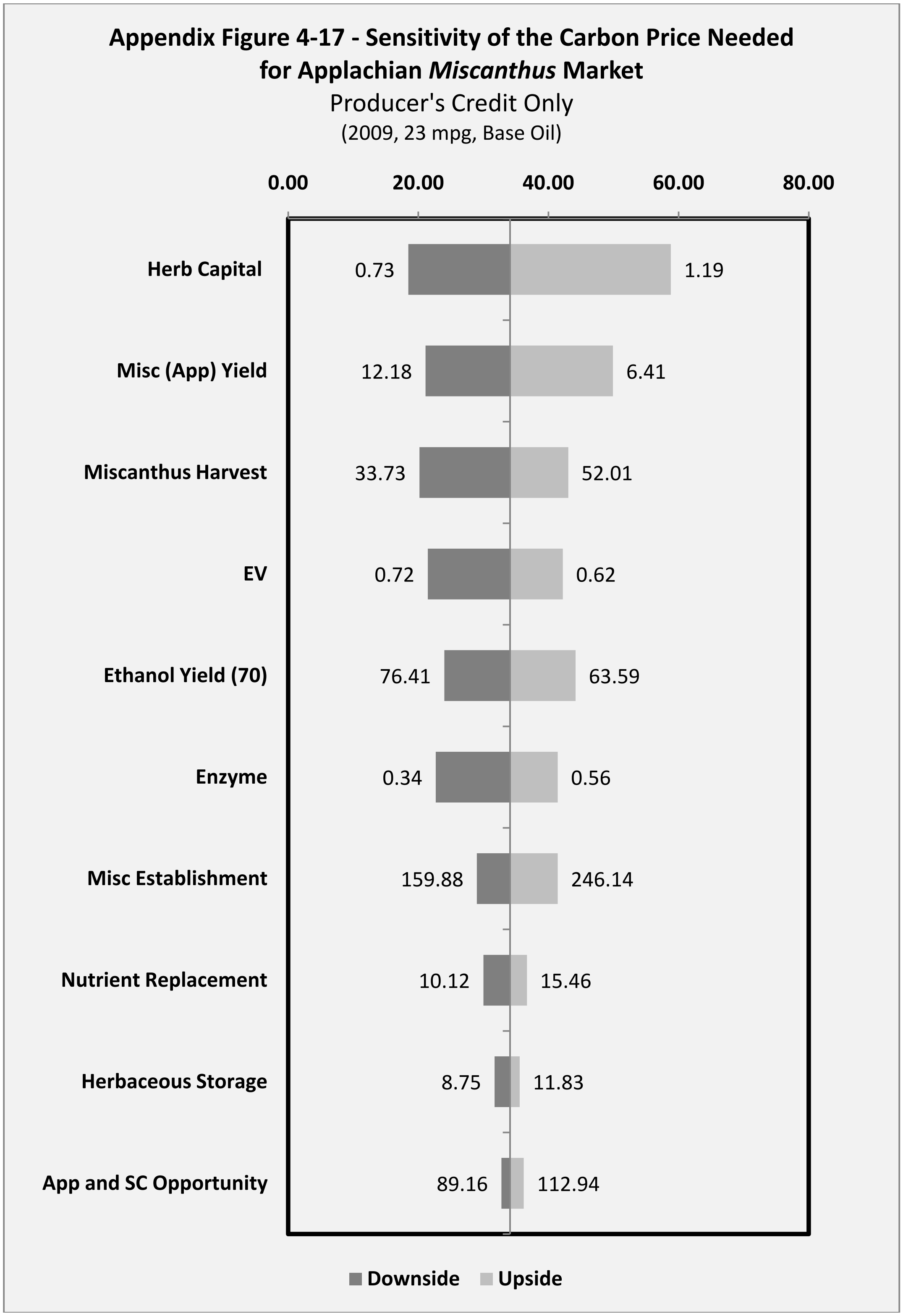
Appendix Figure 4-13 - Sensitivity of Carbon Price Needed for Midwest Switchgrass Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
0.00
50.00
100.00
150.00
SG (MW) Yield
5.85
2.48
Herb Capital
0.73
1.19
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
SG/Straw/PG Harvest
28.15
40.34
MW Opportunity
138.04
163.18
SG Establishment
89.17
113.02
Nutrient Replacement
10.12
15.46
Herbaceous Storage
8.75
11.83
Downside
Upside

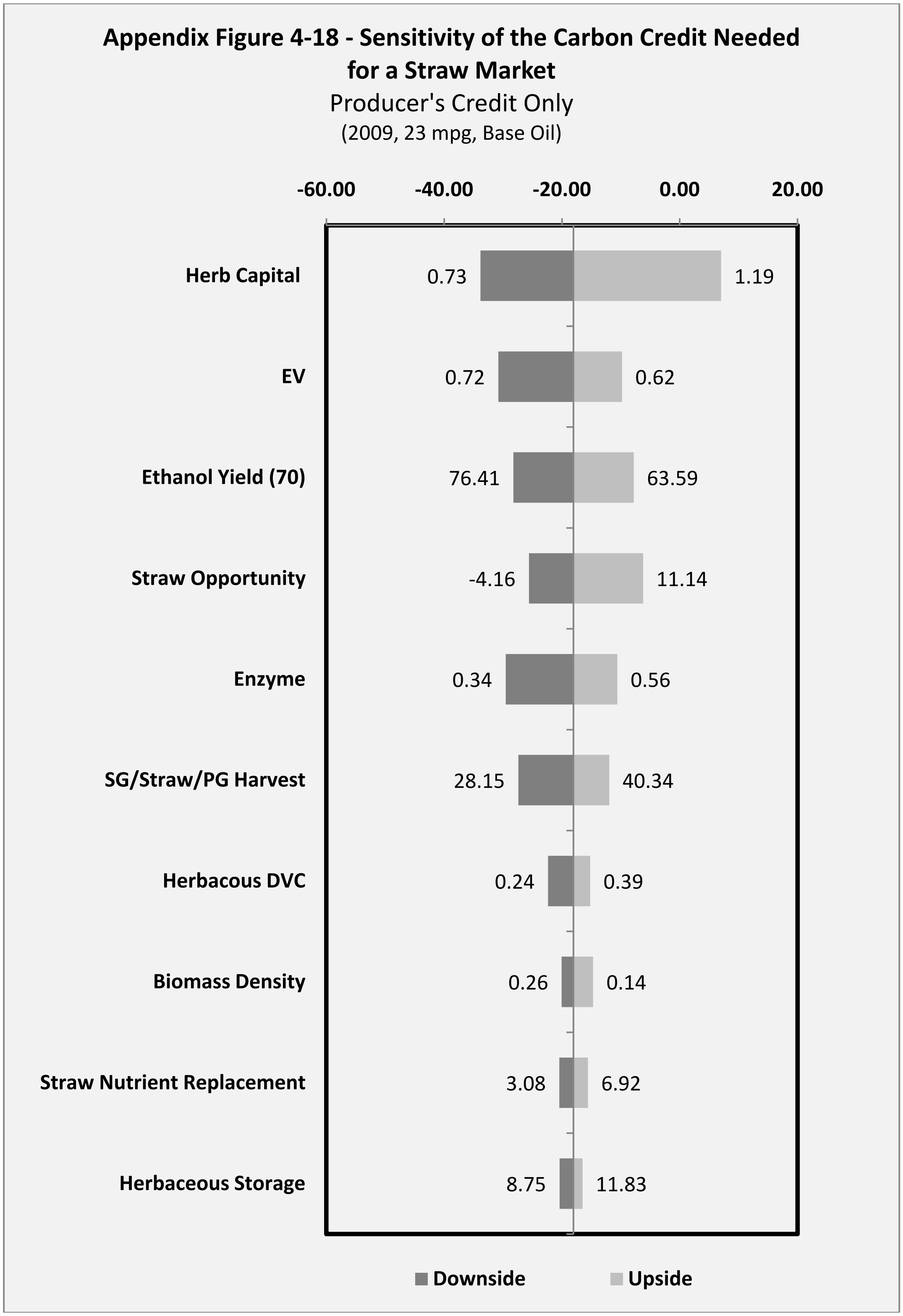

Appendix Figure 4-14 - Sensitivity of the Carbon Price Needed
for Appalachian Switchgrass Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
-20.00
0.00
20.00
40.00
60.00
80.00
SG (App) Yield
8.94
3.54
Herb Capital
0.73
1.19
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
SG/Straw/PG Harvest
28.15
40.34
Nutrient Replacement
10.12
15.46
SG Establishment
89.17
113.02
App and SC Opportunity
89.16
112.94
Herbaceous Storage
8.75
11.83
Downside
Upside


Appendix Figure 4-15 - Sensitivity of Carbon Price Needed for South-Central Switchgrass Market
Producer's Credit
(2009, 23 mpg, Base Oil)
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
SG (SC) Yield
8.50
2.99
Herb Capital
0.73
1.19
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
SG/Straw/PG Harvest
28.15
40.34
Nutrient Replacement
10.12
15.46
SG Establishment
89.17
113.02
App and SC Opportunity
89.16
112.94
Herbaceous Storage
8.75
11.83
Downside
Upside

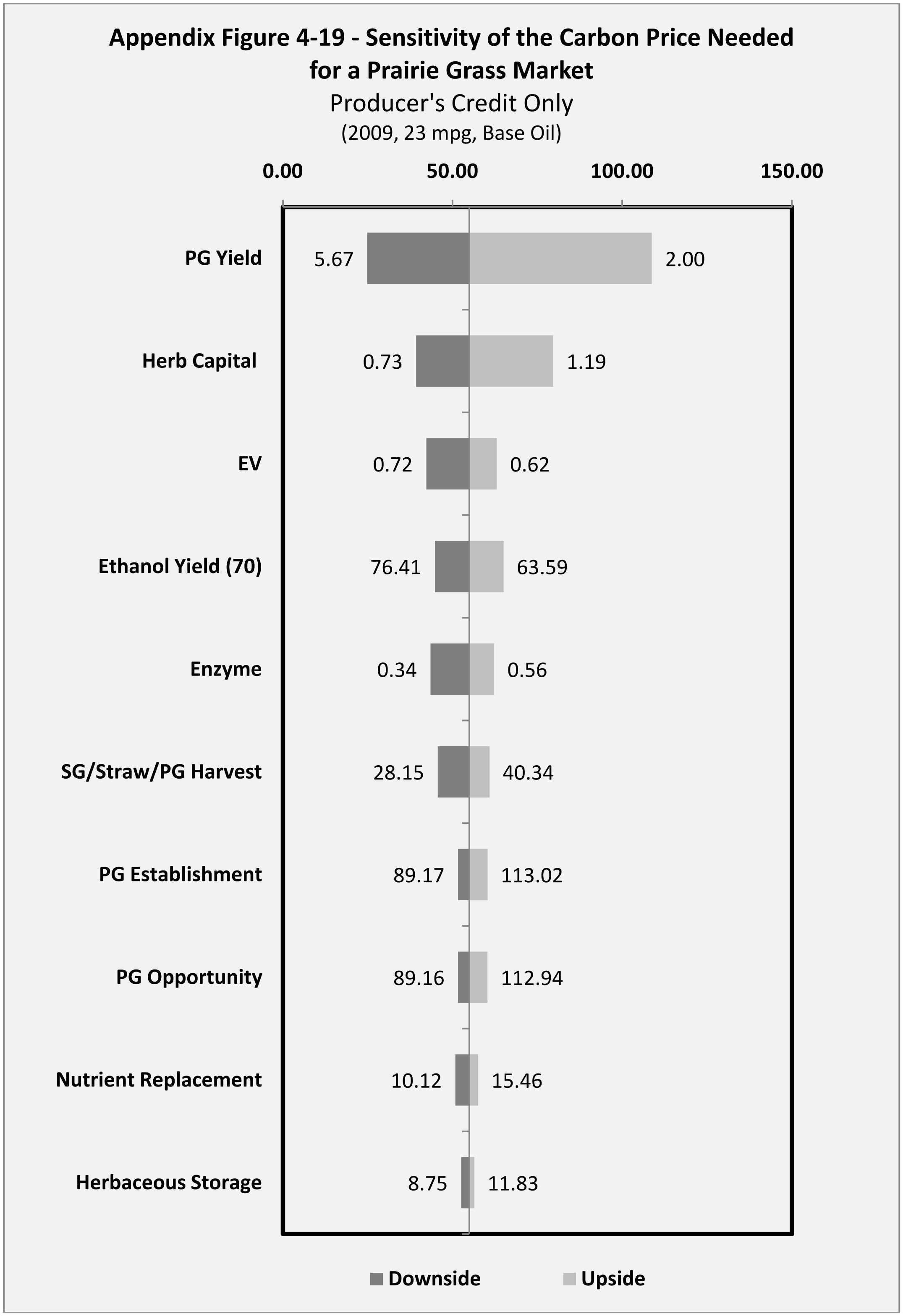


Appendix Figure 4-16 - Sensitivity of the Carbon Price Needed for Midwest *Miscanthus* Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
20.00
40.00
60.00
80.00
100.00
120.00
Misc (MW) Yield
9.53
4.00
Herb Capital
0.73
1.19
Miscanthus Harvest
33.73
52.01
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
Misc Establishment
159.88
246.14
Nutrient Replacement
10.12
15.46
MW Opportunity
138.04
163.18
Herbaceous Storage
8.75
11.83
Downside
Upside


Appendix Figure 4-17 - Sensitivity of the Carbon Price Needed
for Applachian *Miscanthus* Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
0.00
20.00
40.00
60.00
80.00
Herb Capital
0.73
1.19
Misc (App) Yield
12.18
6.41
Miscanthus Harvest
33.73
52.01
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
Misc Establishment
159.88
246.14
Nutrient Replacement
10.12
15.46
Herbaceous Storage
8.75
11.83
App and SC Opportunity
89.16
112.94
Downside
Upside



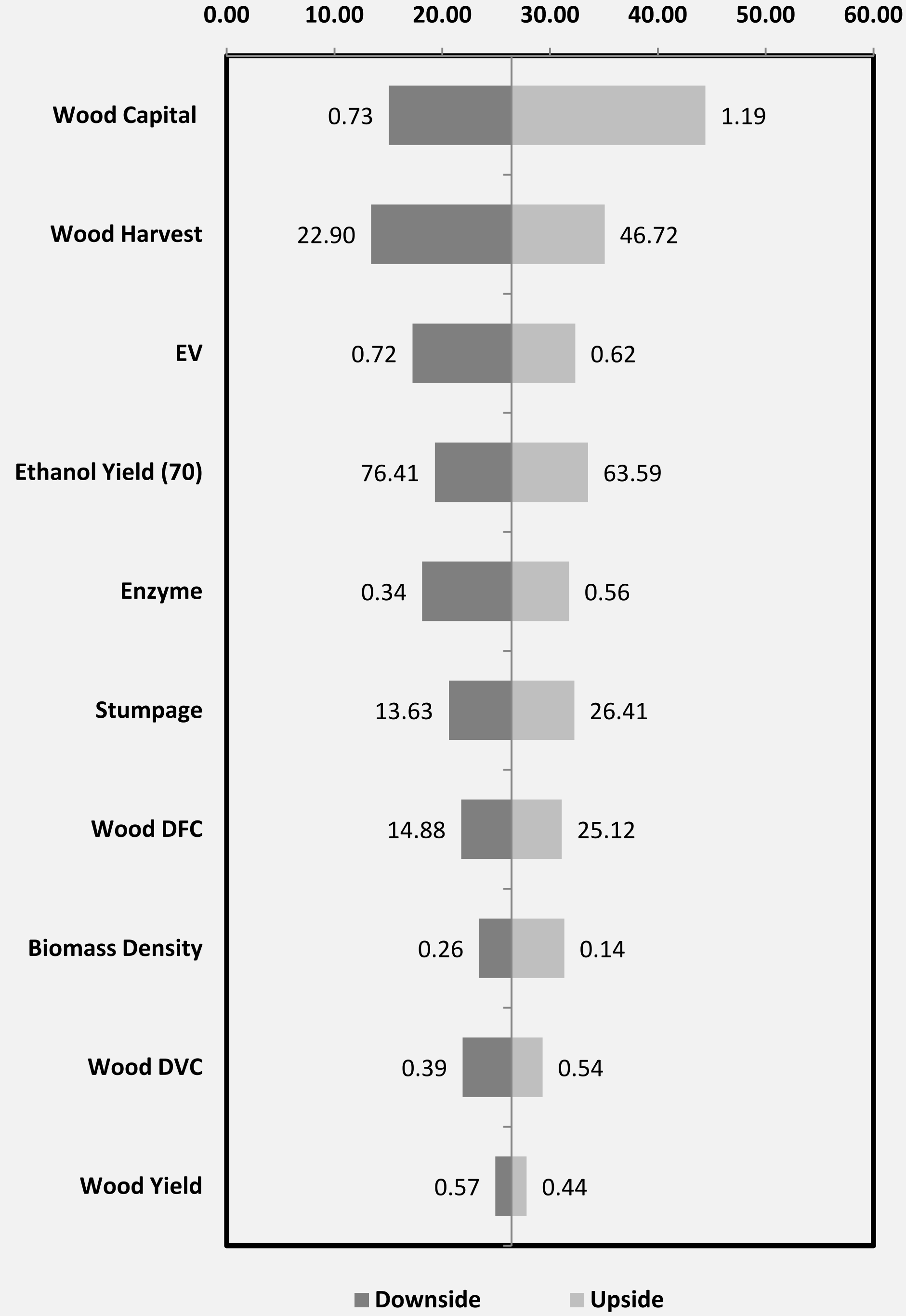
Appendix Figure 4-18 - Sensitivity of the Carbon Credit Needed for a Straw Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
-60.00
-40.00
-20.00
0.00
20.00
Herb Capital
0.73
1.19
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Straw Opportunity
-4.16
11.14
Enzyme
0.34
0.56
SG/Straw/PG Harvest
28.15
40.34
Herbacous DVC
0.24
0.39
Biomass Density
0.26
0.14
Straw Nutrient Replacement
3.08
6.92
Herbaceous Storage
8.75
11.83
Downside
Upside

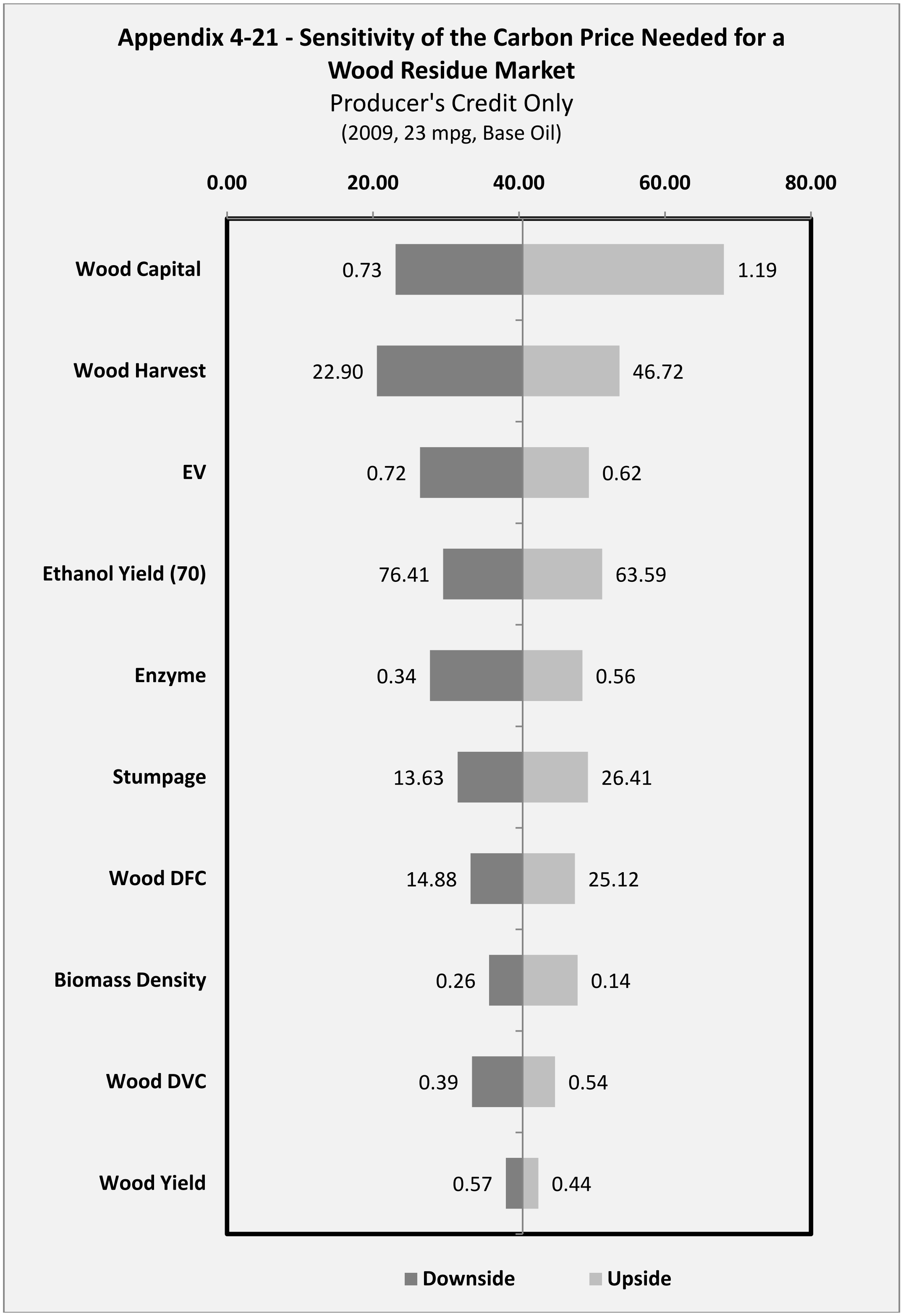

Appendix Figure 4-19 - Sensitivity of the Carbon Price Needed for a Prairie Grass Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
0.00
50.00
100.00
150.00
PG Yield
5.67
2.00
Herb Capital
0.73
1.19
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
SG/Straw/PG Harvest
28.15
40.34
PG Establishment
89.17
113.02
PG Opportunity
89.16
112.94
Nutrient Replacement
10.12
15.46
Herbaceous Storage
8.75
11.83
Downside
Upside

Appendix Figure 4-20 - Sensitivity of the Carbon Price Needed for Farmed Wood Market

Producer's Credit Only

(2009, 23 mpg, Base Oil)




Appendix 4-21 - Sensitivity of the Carbon Price Needed for a Wood Residue Market
Producer's Credit Only
(2009, 23 mpg, Base Oil)
0.00
20.00
40.00
60.00
80.00
Wood Capital
0.73
1.19
Wood Harvest
22.90
46.72
EV
0.72
0.62
Ethanol Yield (70)
76.41
63.59
Enzyme
0.34
0.56
Stumpage
13.63
26.41
Wood DFC
14.88
25.12
Biomass Density
0.26
0.14
Wood DVC
0.39
0.54
Wood Yield
0.57
0.44
Downside
Upside